Model Building for Future

Community Summer Study

SN WMASS

July 17-26 2022, Seattle

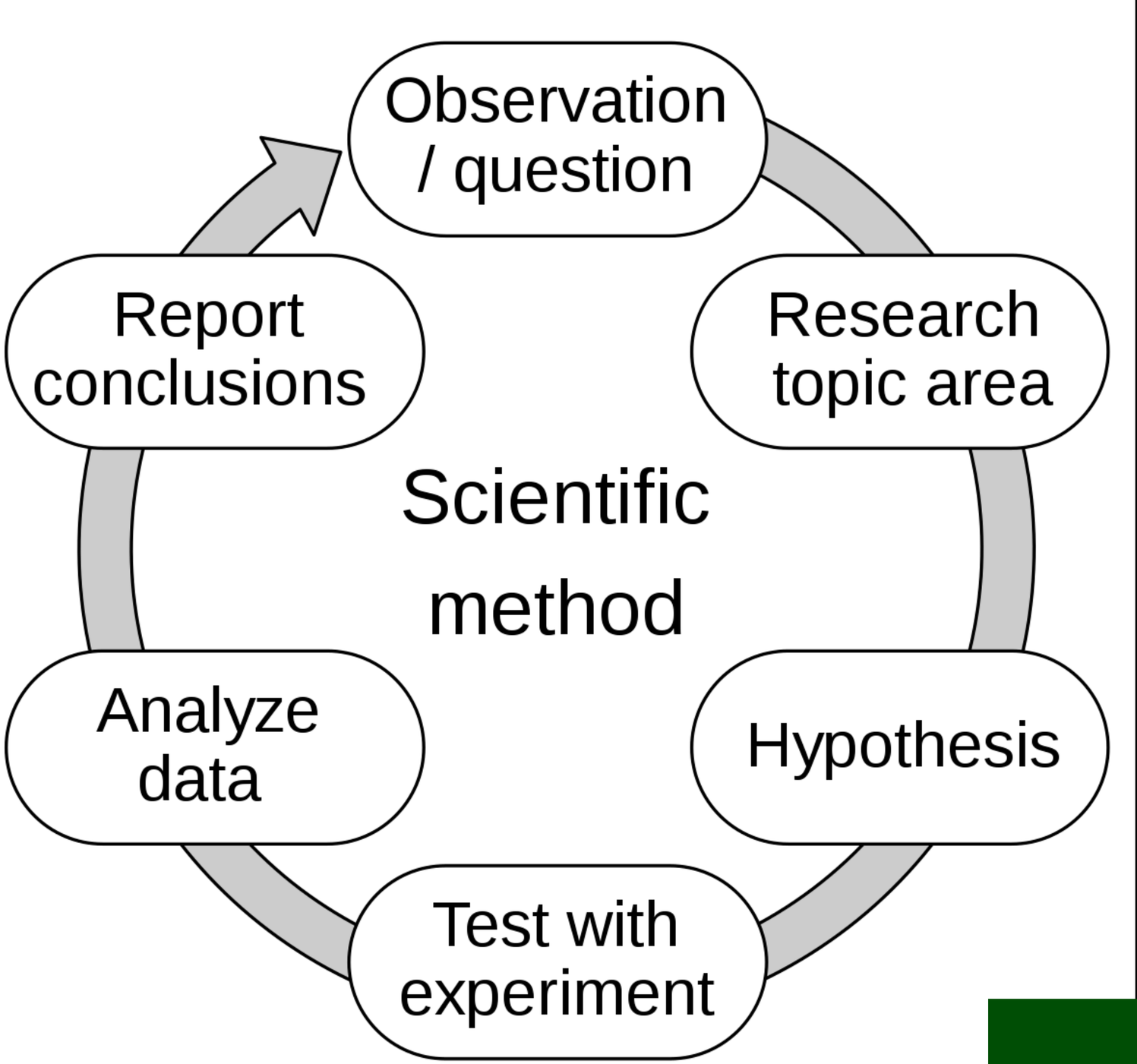
Hitoshi Murayama (UC Berkeley, LBNL, Kavli IPMU)

July 23, 2022

Caption Box

What is “Model Building”?

The scientific method is often represented as an ongoing process. This diagram represents one variant, and there are many others.



Wikipedia

Caption Box

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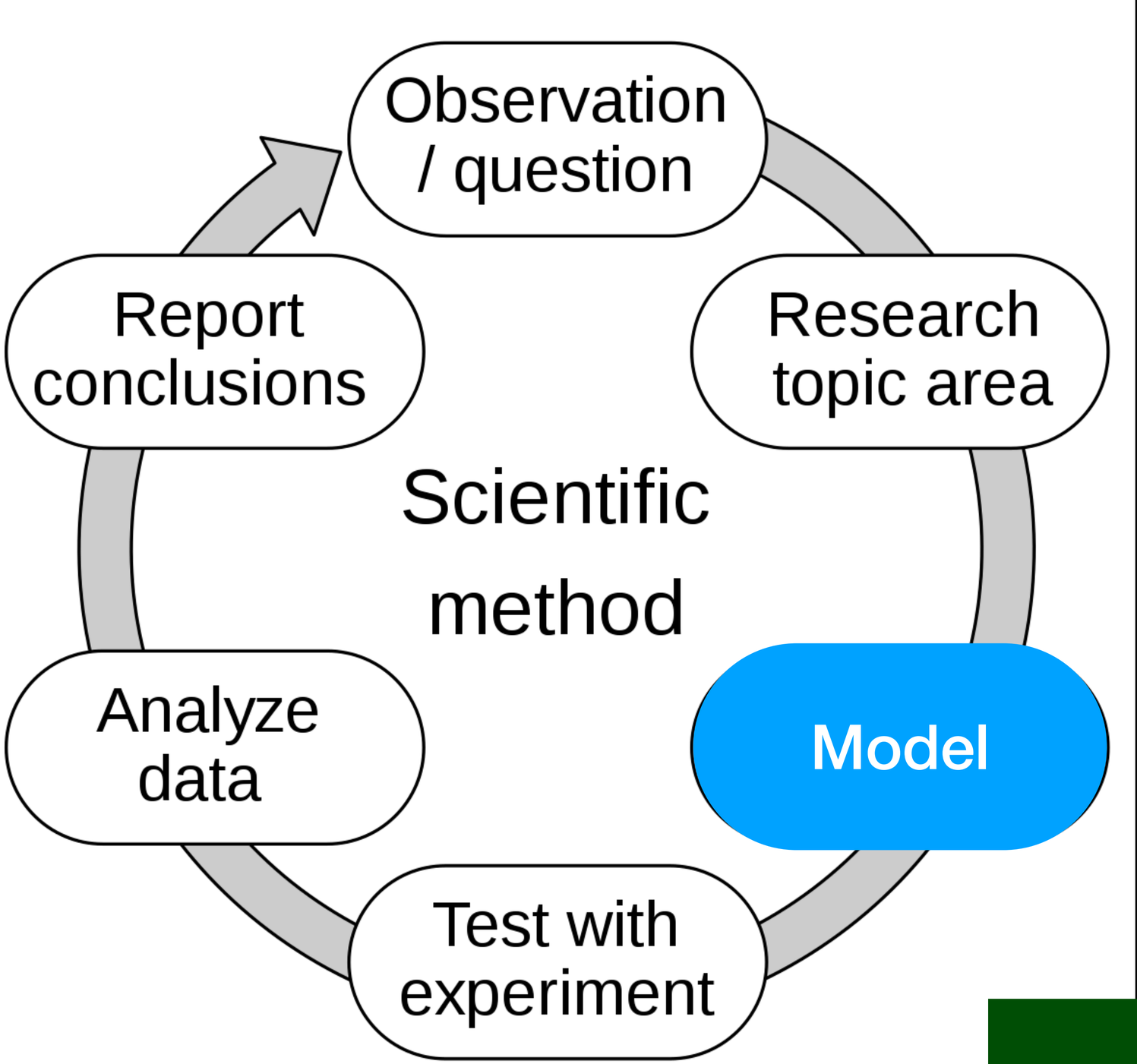

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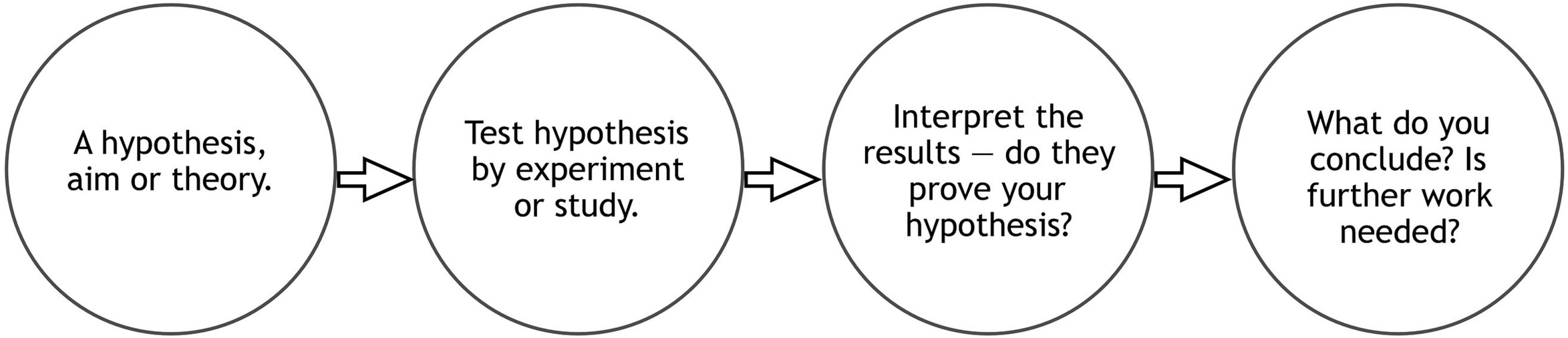

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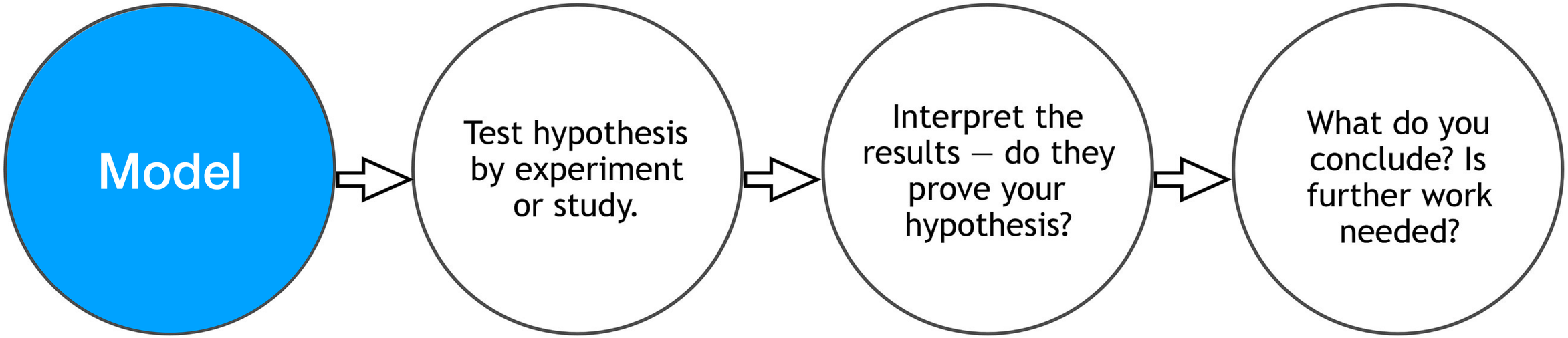

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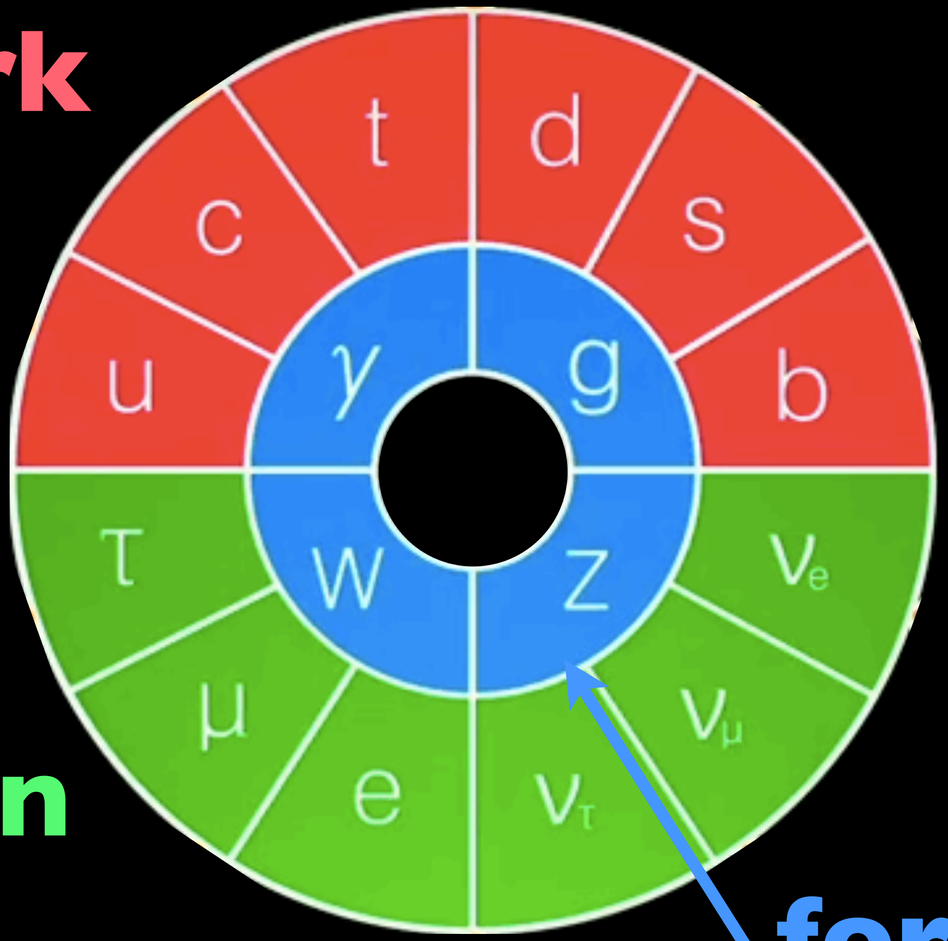
Caption Box

Standard Model

quark



lepton

force carriers

**Fermi, Yukawa,
Nambu–Jona-Lasinio,
Brout-Englert, Higgs,
Gell-Mann–Lévy, Cabibbo,
Sudarshan–Marshak, Gell-Mann–Feynman
Glashow, Weinberg, Salam,
Glashow–Illiopoulos–Maiani,
Kobayashi–Maskawa,
Pontecoro, Maki–Nakagawa–Sakita,
and many more**

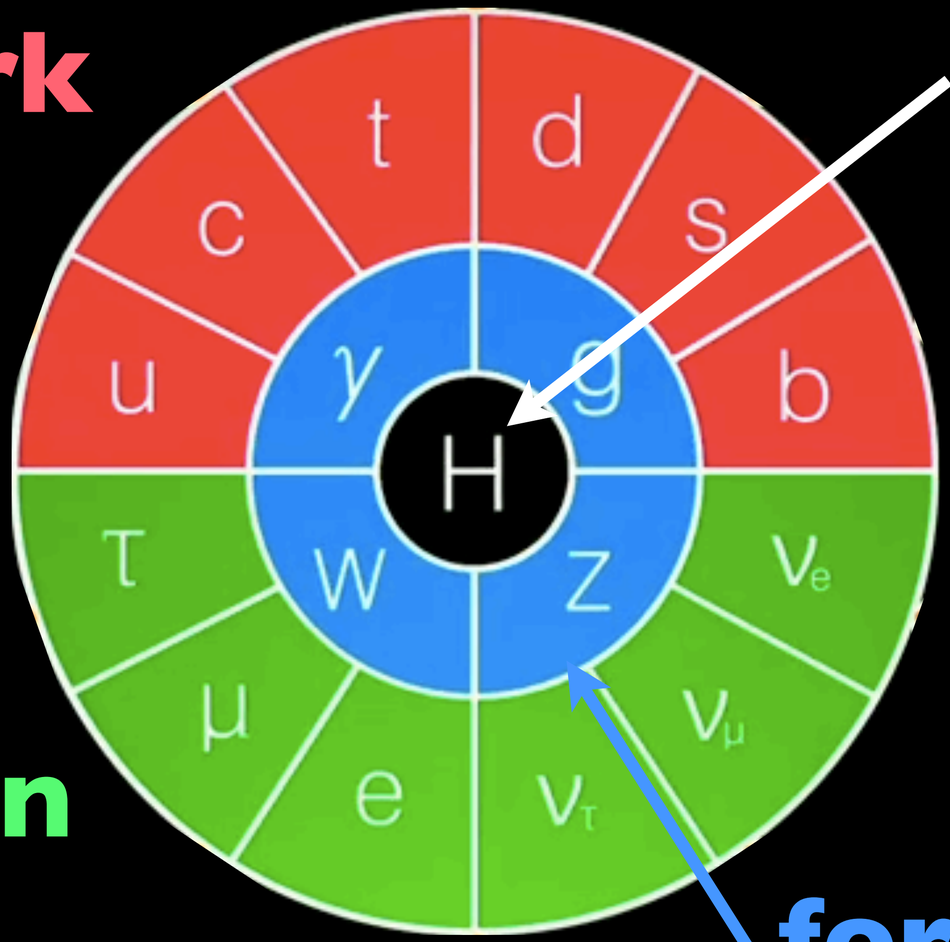
**Standard Model was built by community,
not a *"lone genius"***

Caption Box

Standard Model

quark

lepton



Higgs

Fermi, Yukawa,
Nambu–Jona-Lasinio,
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Standard Model

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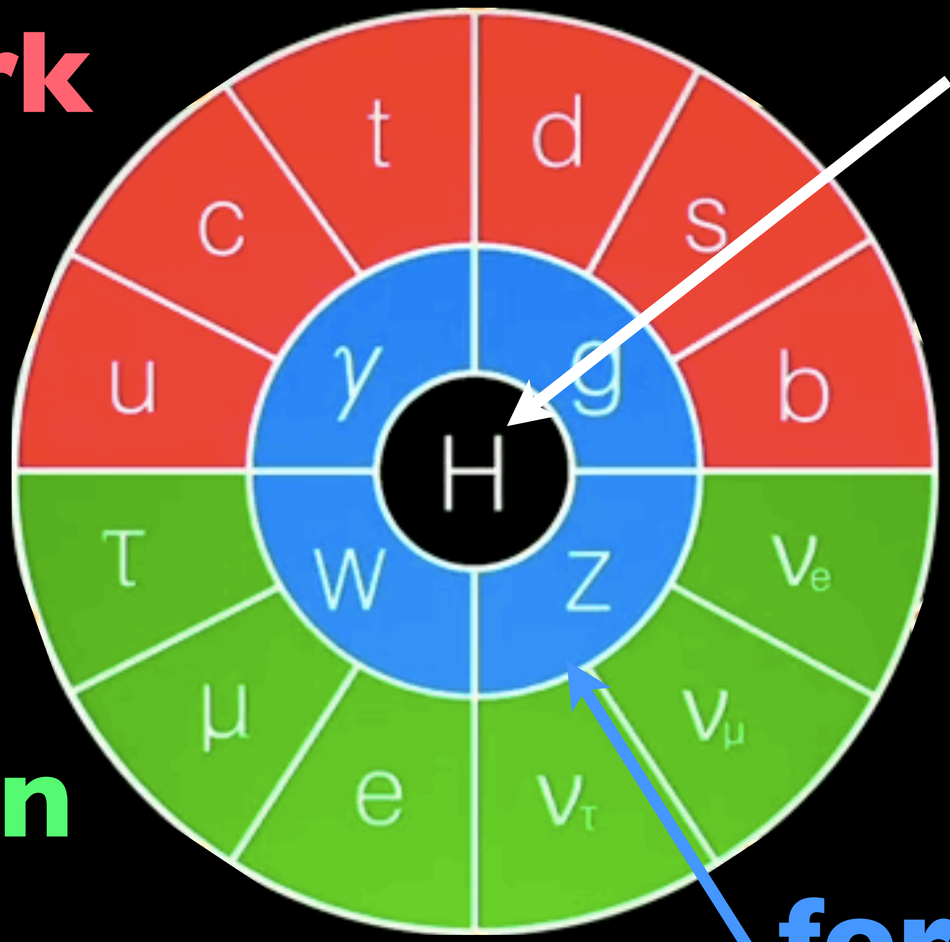

**Culmination of physics
from discovery of electron to Higgs
spanning 115 years
Milestone in Physics!**

**Fermi, Yukawa,
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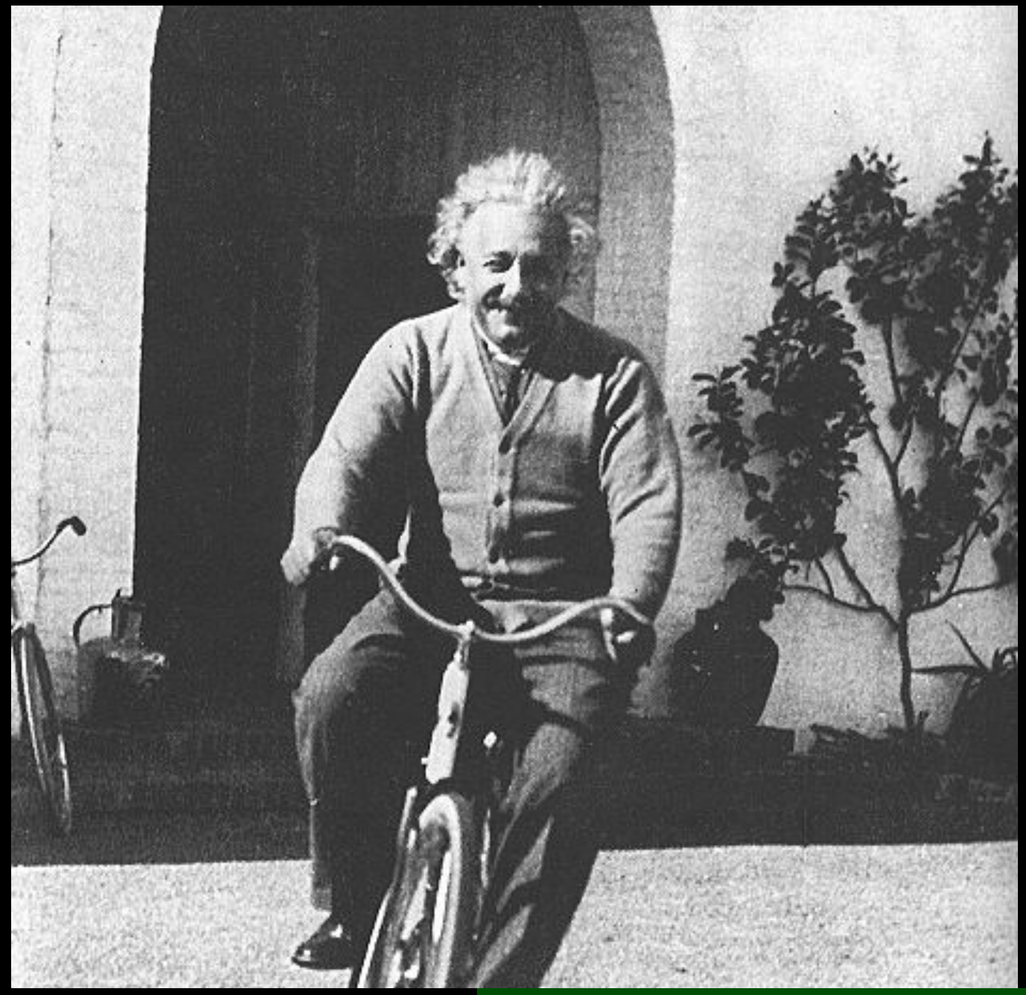
©Particle Fever

Caption Box

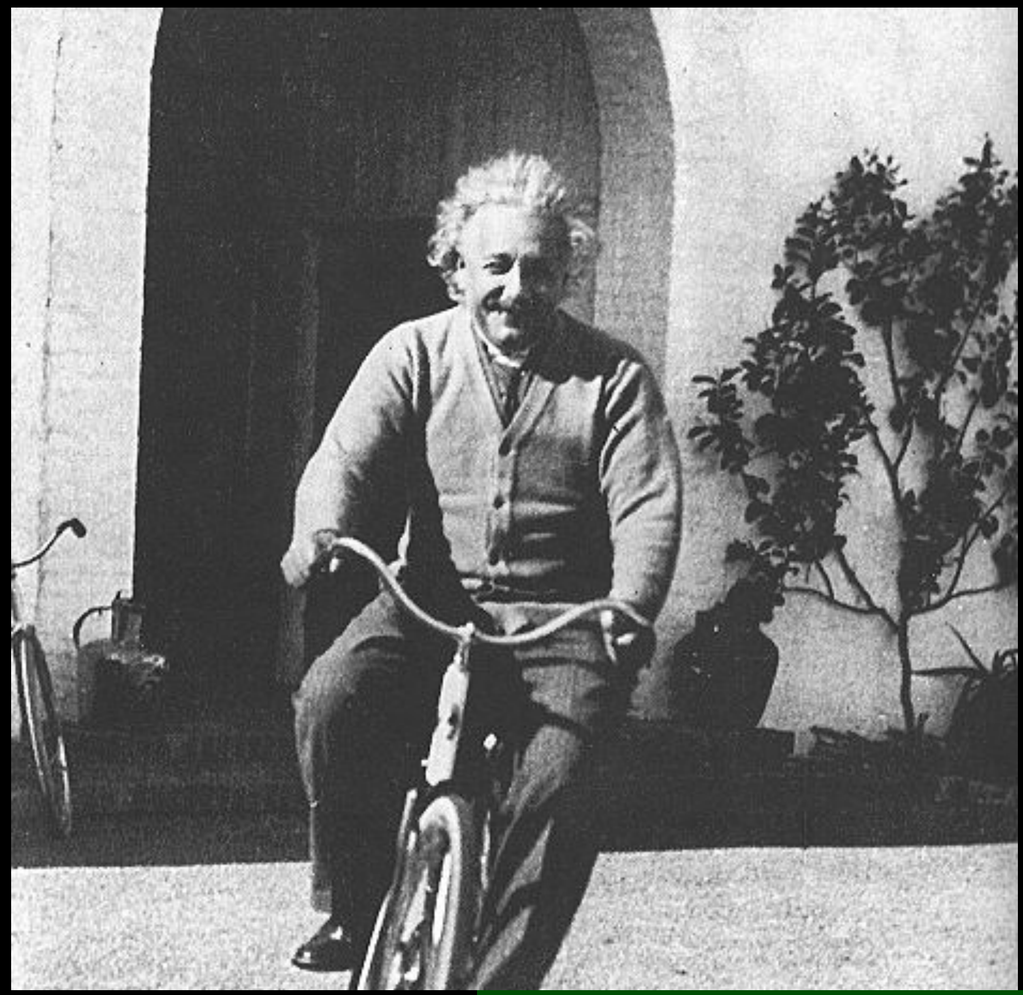
Einstein’s Dream



Caption Box

Einstein’s Dream

- Is there an underlying simplicity behind vast phenomena in Nature?



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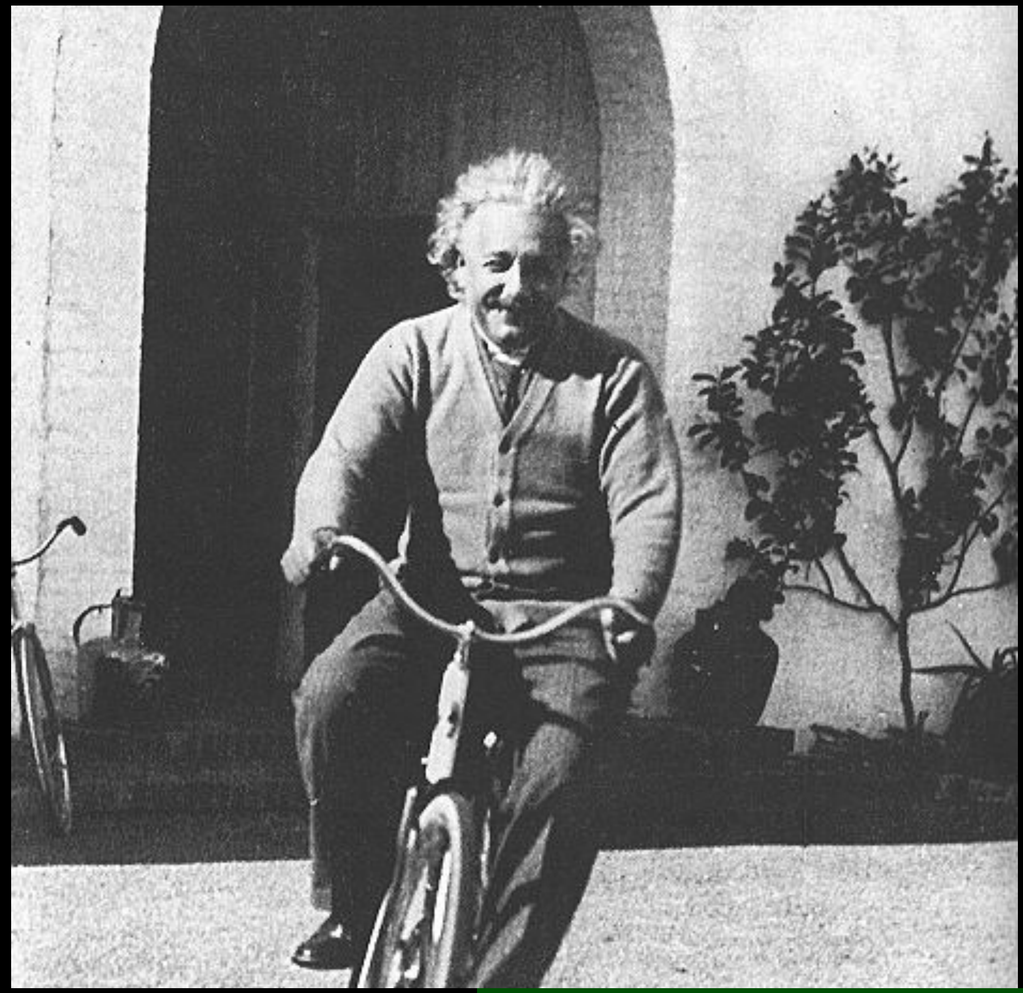
Einstein’s Dream

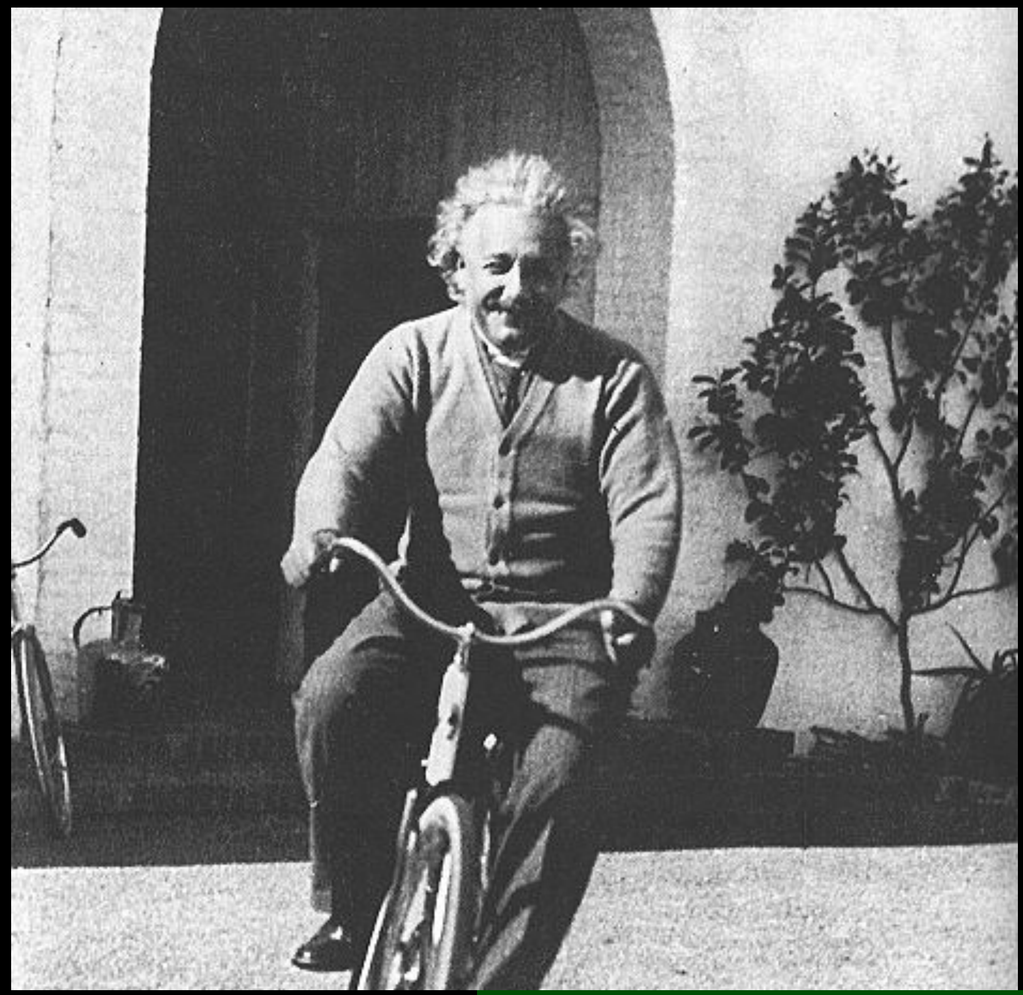
- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description



Caption Box

Einstein’s Dream

- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description
- But he failed to unify electromagnetism and gravity (GR)

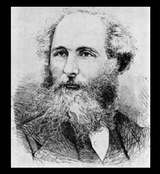


Caption Box

History of Unification

planets *apple*

gravity *mechanics*



electric *magnetic*

electromagnetism

atoms

Quantum mechanics

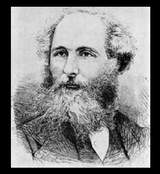
γ-*decay*

β-*decay*

α-*decay*

Caption Box

History of Unification



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Caption Box

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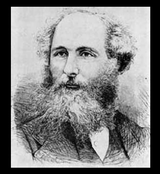

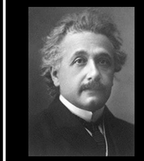

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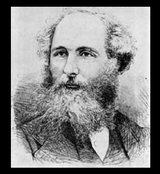
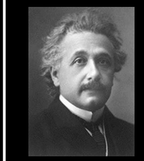




planets apple

electric magnetic

atoms

electromagnetism

Quantum mechanics

gravity mechanics

γ-decay

Special relativity

β-decay

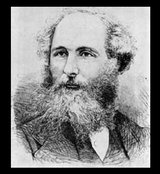
GR

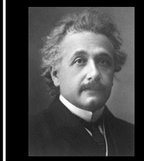
~10⁻⁸cm Quantum ElectroDynamics

α-decay

Caption Box

History of Unification





planets *apple*

gravity *mechanics*

GR

electric *magnetic*

electromagnetism

Special relativity

~10^{-8}cm *Quantum ElectroDynamics*

atoms

Quantum mechanics

γ-*decay*

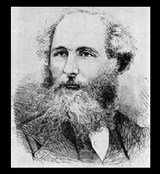
β-*decay*

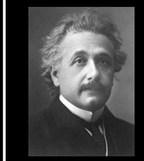
α-*decay*

Strong Force

Caption Box

History of Unification





planets apple

electric magnetic

atoms

electromagnetism

Quantum mechanics

gravity mechanics

γ-decay

Special relativity

GR

~10⁻⁸cm Quantum ElectroDynamics

β-decay

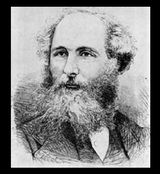
α-decay

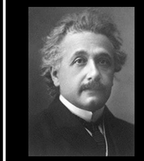
Weak force

Strong Force

Caption Box

History of Unification





planets *apple*

gravity *mechanics*

electric *magnetic*

electromagnetism

atoms

Quantum mechanics

γ-decay

Special relativity

GR

~10⁻⁸cm *Quantum ElectroDynamics*

β-decay

α-decay

Weak force

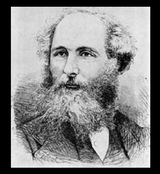
Electroweak theory

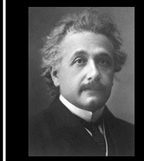
~10⁻¹⁶cm

Strong Force

Caption Box

History of Unification





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~10⁻⁸cm *Quantum ElectroDynamics*

β-decay

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Weak force

Electroweak theory

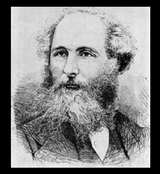
~10⁻¹⁶cm

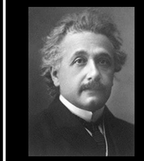
Strong Force

hadrons

Caption Box

History of Unification





planets *apple*

electric *magnetic*

atoms

electromagnetism

Quantum mechanics

gravity *mechanics*

γ-decay

Special relativity

GR

~10⁻⁸cm *Quantum ElectroDynamics*

β-decay

α-decay

Weak force

Electroweak theory
~10⁻¹⁶cm

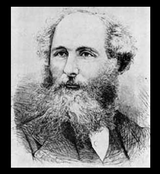
Strong Force

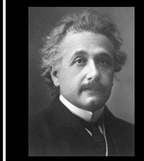
hadrons

jets

Caption Box

History of Unification





planets apple

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Electroweak theory

~10⁻¹⁶cm

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γ-decay

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Weak force

α-decay

Strong Force

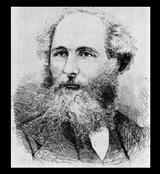
hadrons

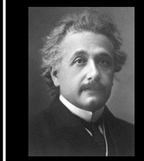
QCD

jets

Caption Box

History of Unification





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Quantum mechanics

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~10⁻⁸cm *Quantum ElectroDynamics*

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Weak force

Electroweak theory

~10⁻¹⁶cm

Strong Force

hadrons

Grand Unification?

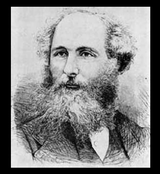
~10⁻³⁰cm

QCD

jets

Caption Box

History of Unification



atoms

electric magnetic

planets apple

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Quantum mechanics

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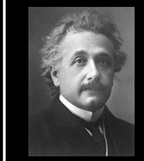

γ-decay

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String theory?

~10⁻³³cm

Grand Unification?

~10⁻³⁰cm

QCD

jets

Caption Box

Five evidences for physics beyond SM

Caption Box

Five evidences for physics beyond SM

- at least five missing pieces in the SM

Caption Box

Five evidences for physics beyond SM

- at least five missing pieces in the SM
  - dark matter

Caption Box

Five evidences for physics beyond SM

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Five evidences for physics beyond SM

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Caption Box

Five evidences for physics beyond SM

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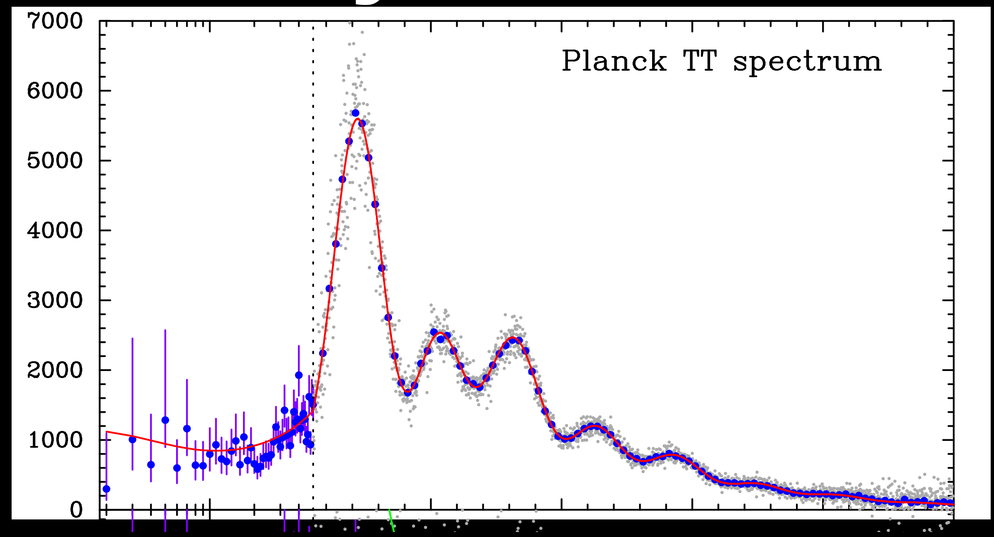
  - dark energy
  - apparently acausal density fluctuations



Caption Box

Five evidences for physics beyond SM

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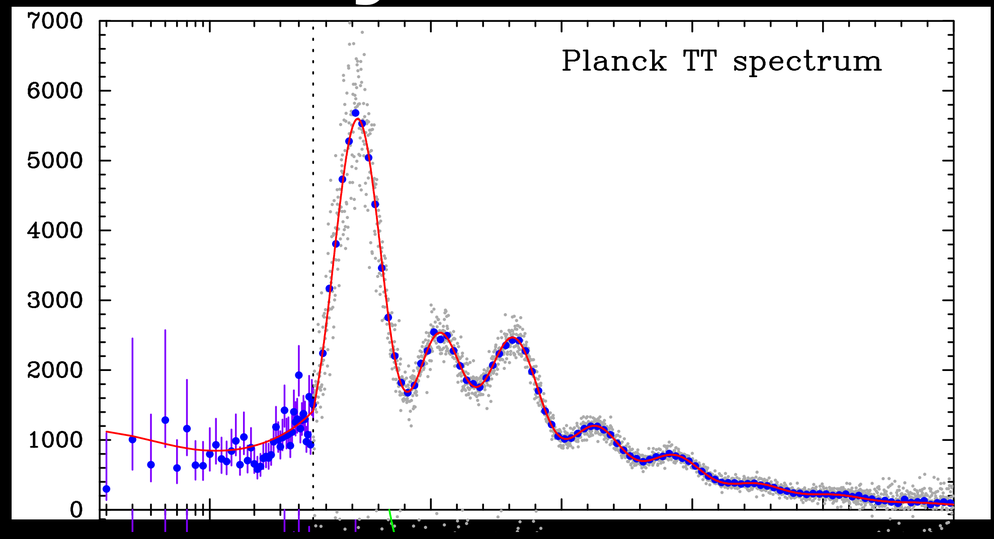
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry



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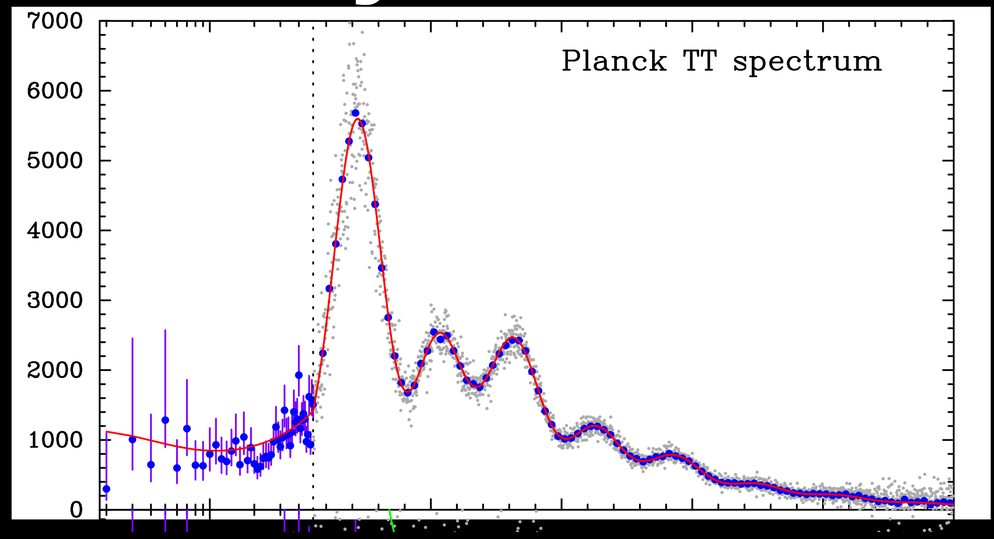

Unusual in science: the problems are clear!

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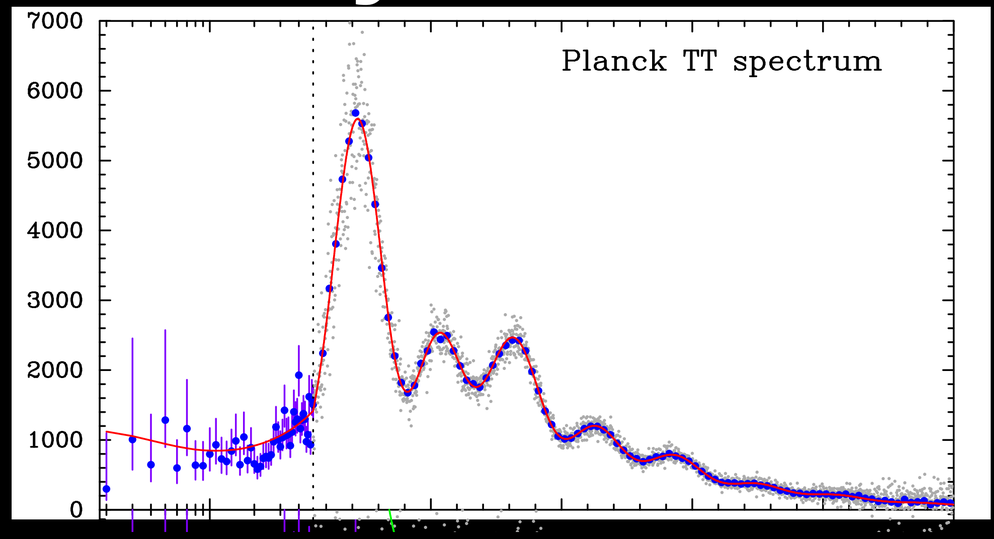

Unusual in science: the problems are clear!

also anomalies (H_0, flavor, g-2, etc)

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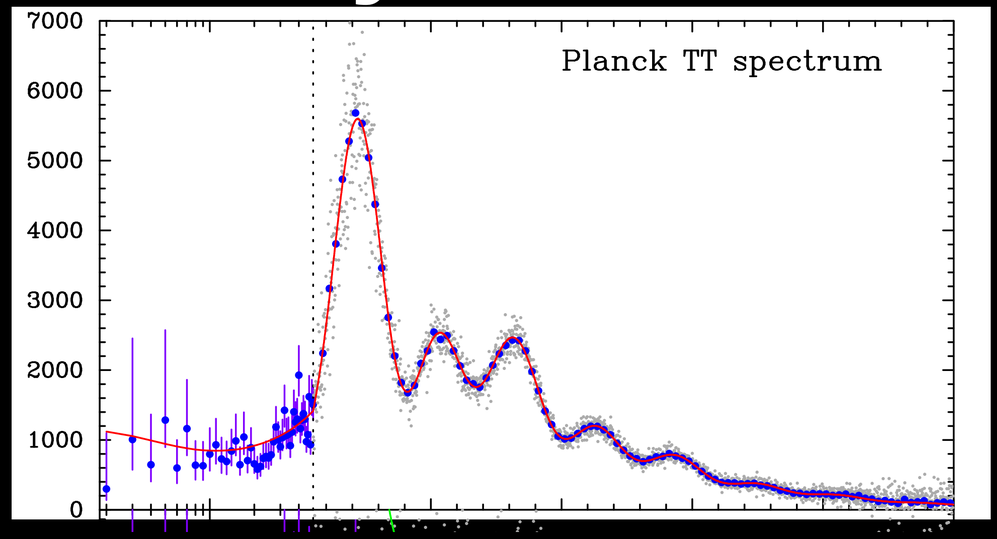

Unusual in science: the problems are clear!

also anomalies (H_0, flavor, g-2, etc)

- theoretical problems:
  - hierarchy problem
  - origin of flavor
  - unification of matter and forces
  - quantum gravity

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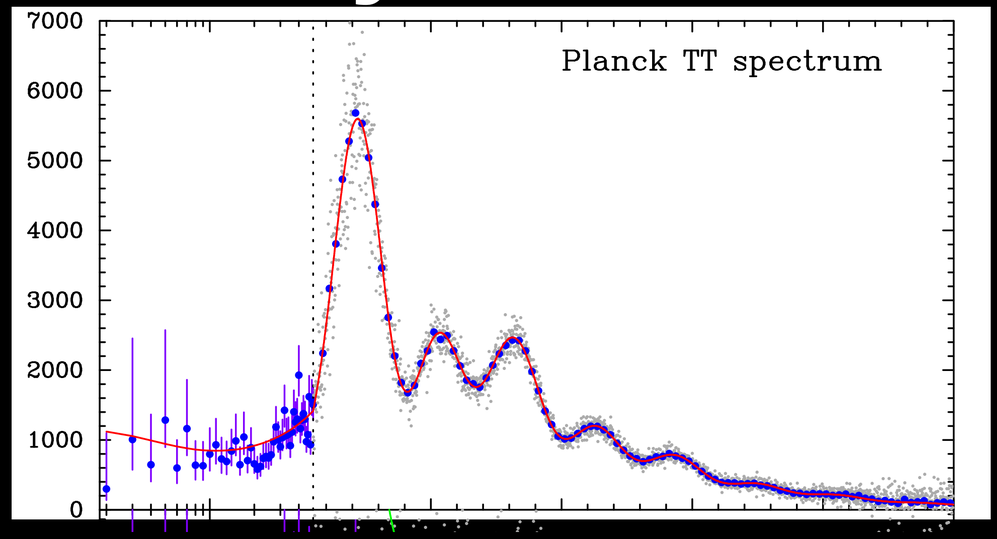

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also anomalies (H_0, flavor, g-2, etc)

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  - unification of matter and forces
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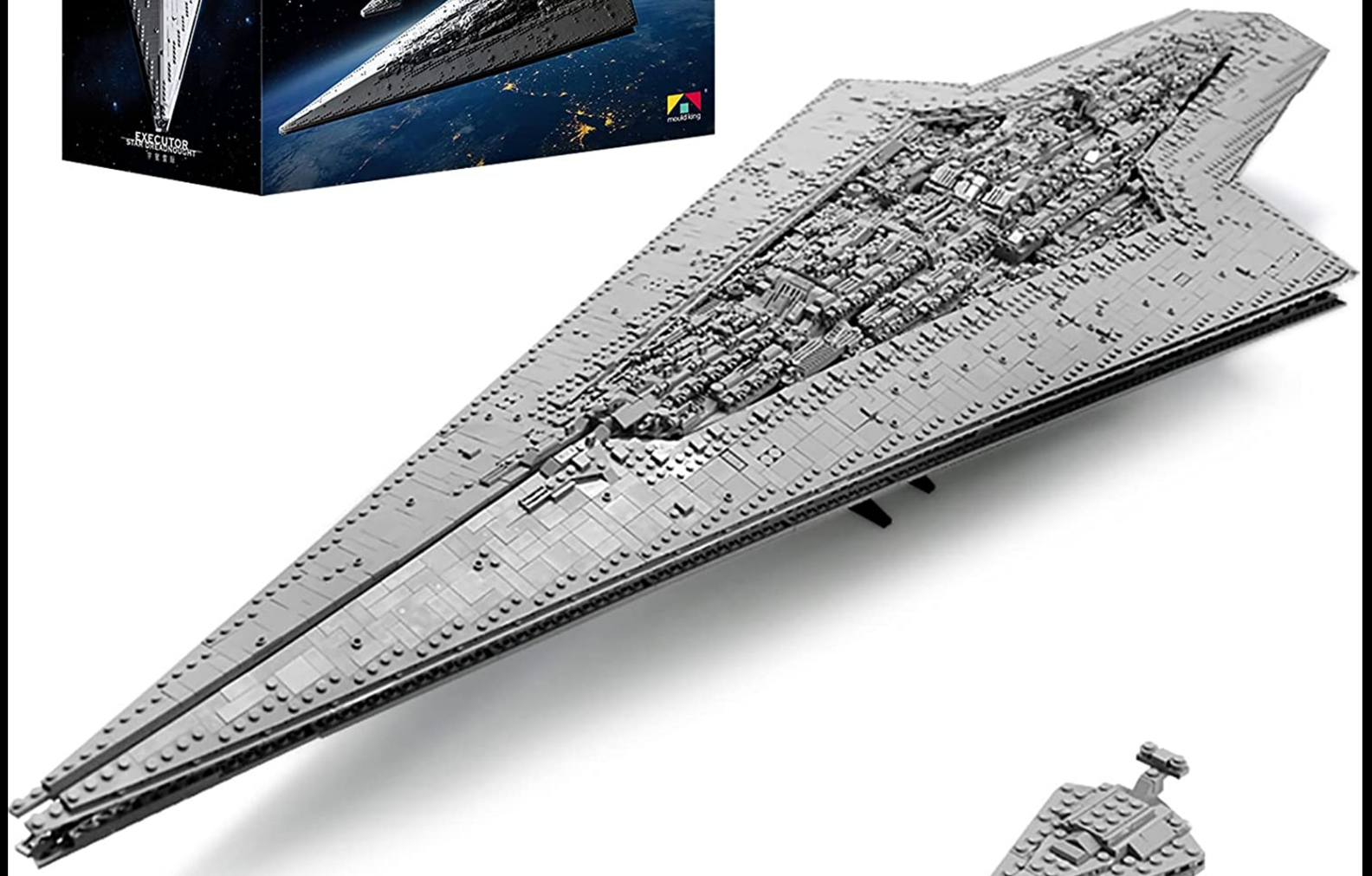
Where is the next energy scale?

Caption Box


MOULD KING
EXECUTOR
STAR DREADNOUGHT
宇宙星际
13134
8+
7588+
mould king



Caption Box

Caption Box

Wikipedia

Caption Box

Wikipedia

Model building is a hobby and career that involves the creation of physical models either from kits or from materials and components acquired by the builder. The kits contain several pieces that need to be assembled in order to make a final model. Most model-building categories have a range of common scales that make them manageable for the average person both to complete and display. A model is generally considered physical representations of an object and maintains accurate relationships between all of its aspects.

Caption Box

Wikipedia

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Caption Box

Lagrangian

Wikipedia

Model building is a hobby and career that involves the creation of physics models either from kits or from materials and components acquired by the builder. The kits contain several pieces that need to be assembled in order to make a final model. Most model-building categories have a range of common scales that make them manageable for the average person both to complete and display. A model is generally considered physical representations of an object and maintains accurate relationships between all of its aspects.

Caption Box

Wikipedia

Lagrangian

Hamiltonian

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our Universe

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Model building is not exclusively a hobbyist pursuit. The complexity of assembling representations of actual objects has become a career for several people, and is heavily applicable in film making. There are, for instance, those who build models/ props to commemorate historic events, employed to construct models using past events as a basis to predict future events of high commercial interest.

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discoveries

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discoveries

Caption Box

Requires skills

The model building kits can be classified according to skill levels that represent the degree of difficulty for the hobbyist. These include skill level 1 with snap-together pieces that do not require glue or paint; skill level 2, which requires glue and paint; and, skill level 3 kits that include smaller and more detailed parts. Advanced skill levels 4 and 5 kits ship with components that have extra-fine details. Particularly, level 5 requires expert-level skills.

Caption Box

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Lagrangian

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non-perturbative dynamics

Caption Box

What do we do?

Our aim

- Write down the Lagrangian that describes the entire Universe
  - At some point we may have to go beyond Lagrangian such as in string theory in quantum spacetime
- should include all success of the SM
  - new particles, new interactions
  - no contradictions with data: collider limits, FCNC, lepton and baryon violation, Neff, dark matter abundance, baryon asymmetry, spectral index, tensor fluctuations, dark energy equation of state, …

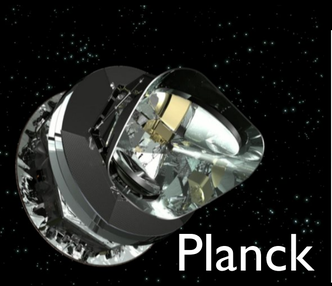
Caption Box

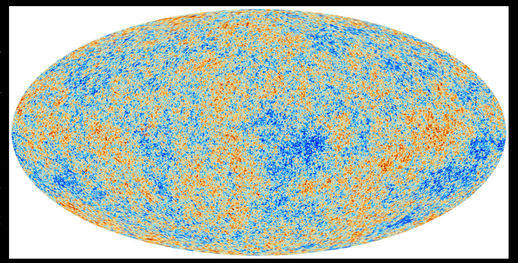
What drives us

- Naturalness
  - Supersymmetry
  - Warped Extra Dimension
  - Neutral Naturalness
  - Cosmological Selection
  - Strong CP and Axions
  - Swampland

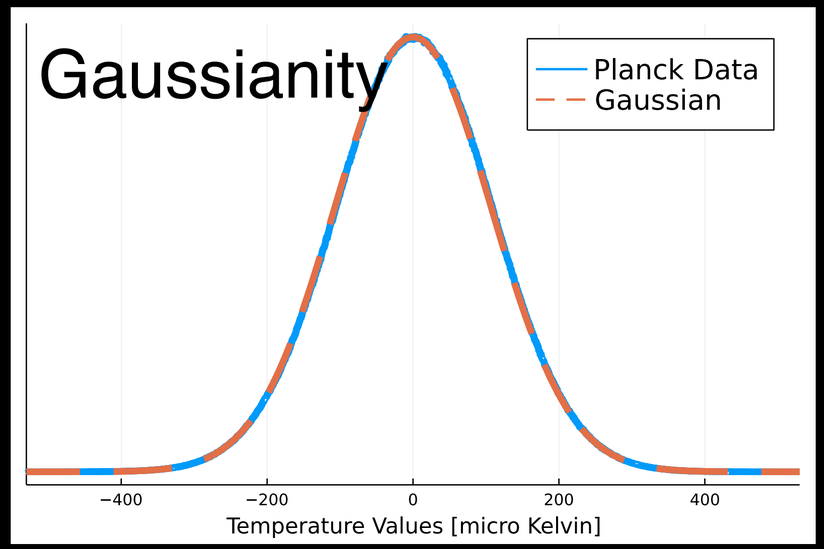
Caption Box

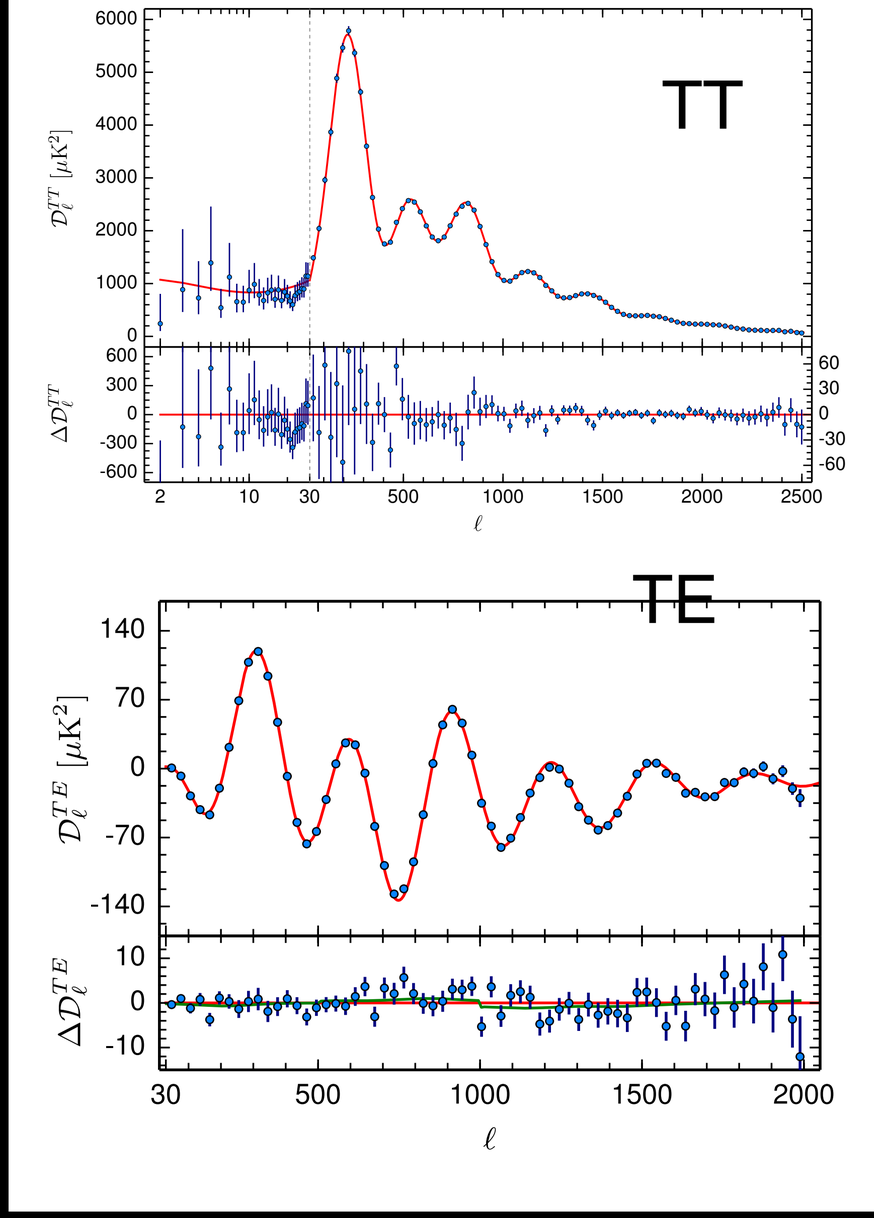
Naturalness works!





- Why is the Universe big?
- Inflation
  - horizon problem
  - flatness problem
  - large entropy

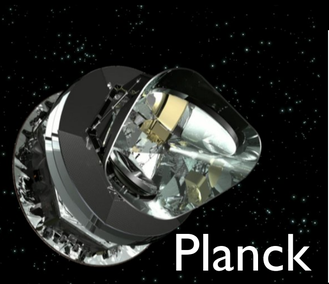




Credit: E. Komatsu

Caption Box

Naturalness



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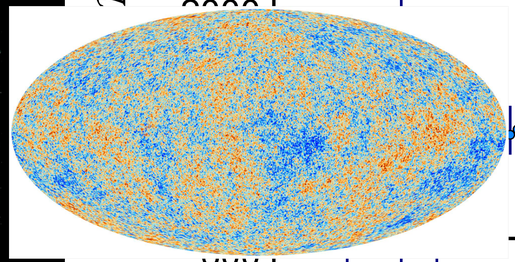
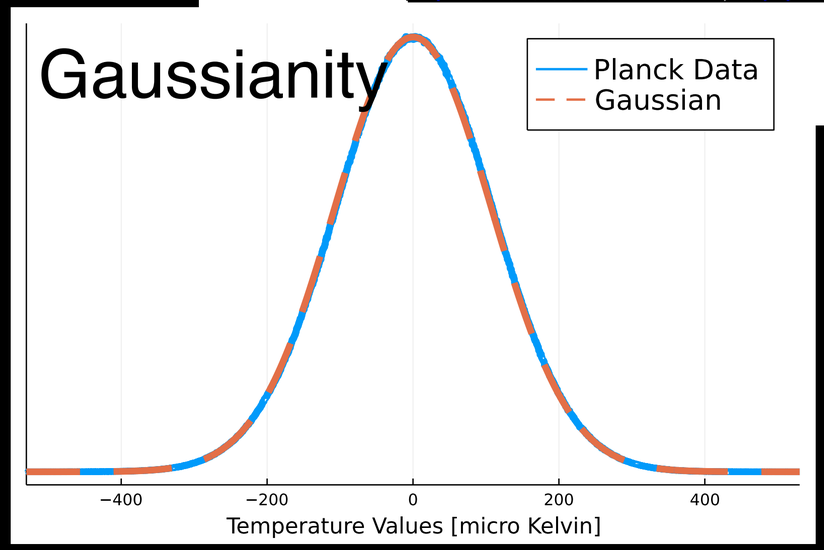
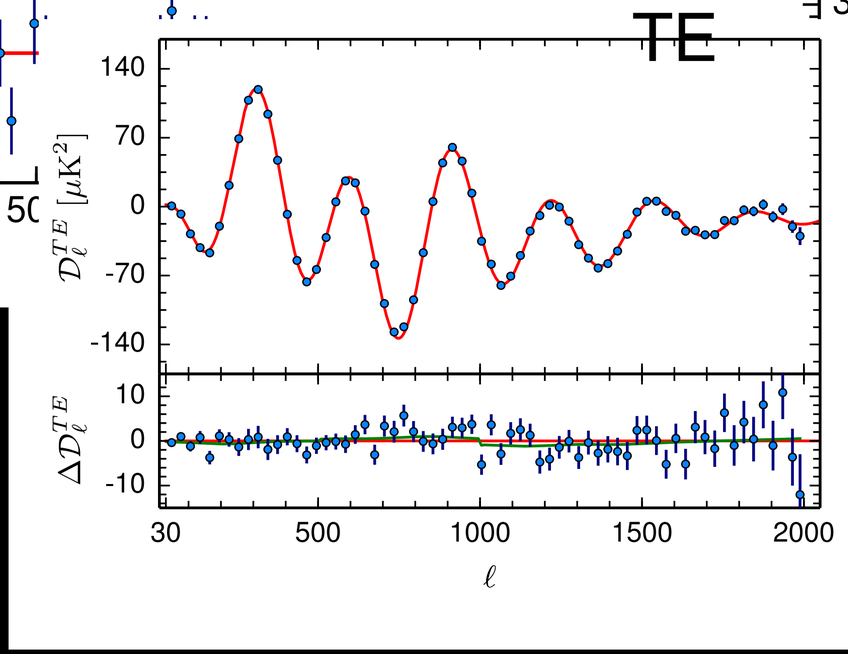






Credit: E. Komatsu

Caption Box

What drives us

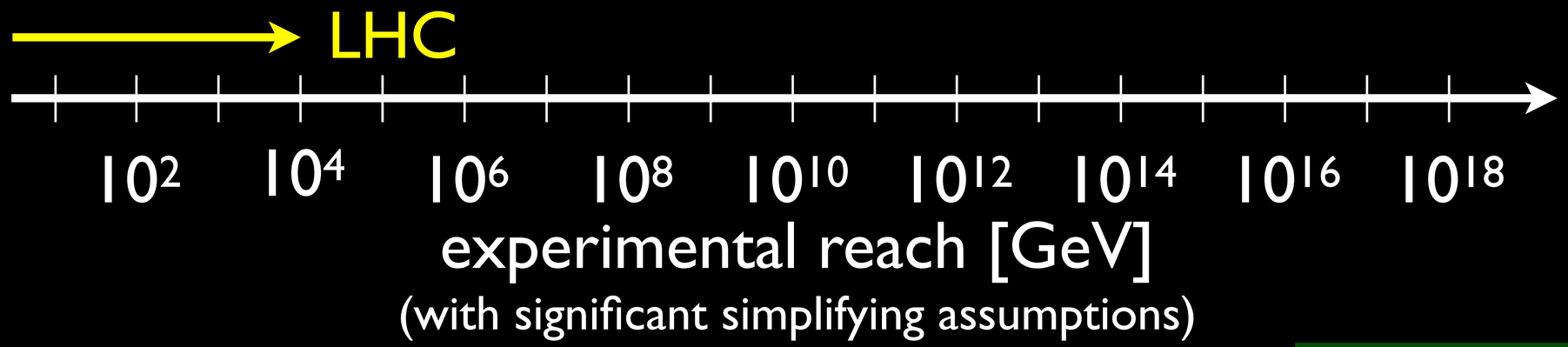
- Dark Matter
  - Interaction Mechanisms
  - Models
- Baryogenesis
- Flavor Model
- Inflation

Caption Box

Power of Expedition

Caption Box

Power of Expedition



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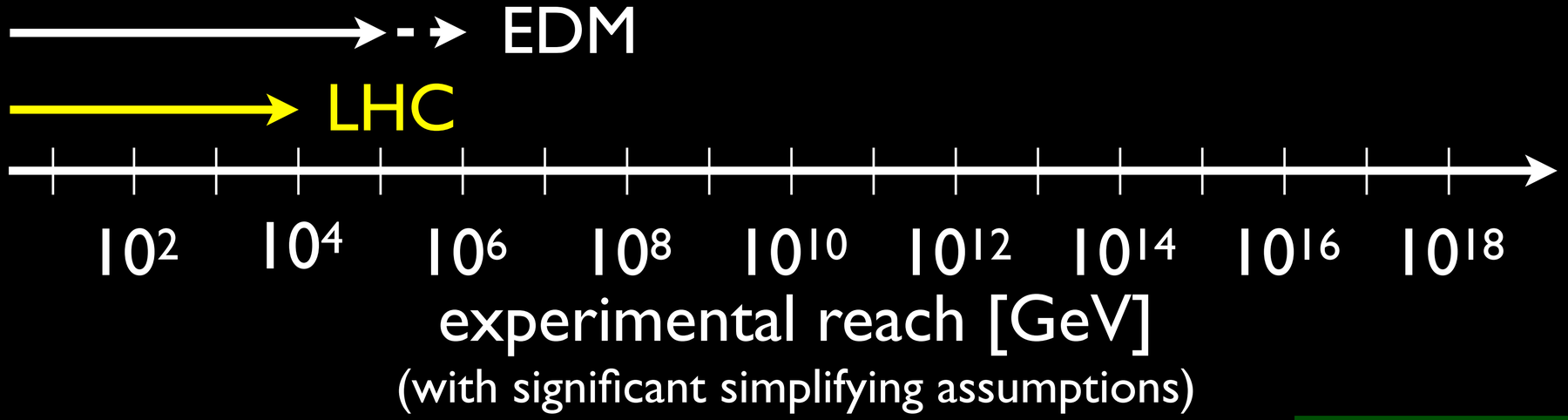

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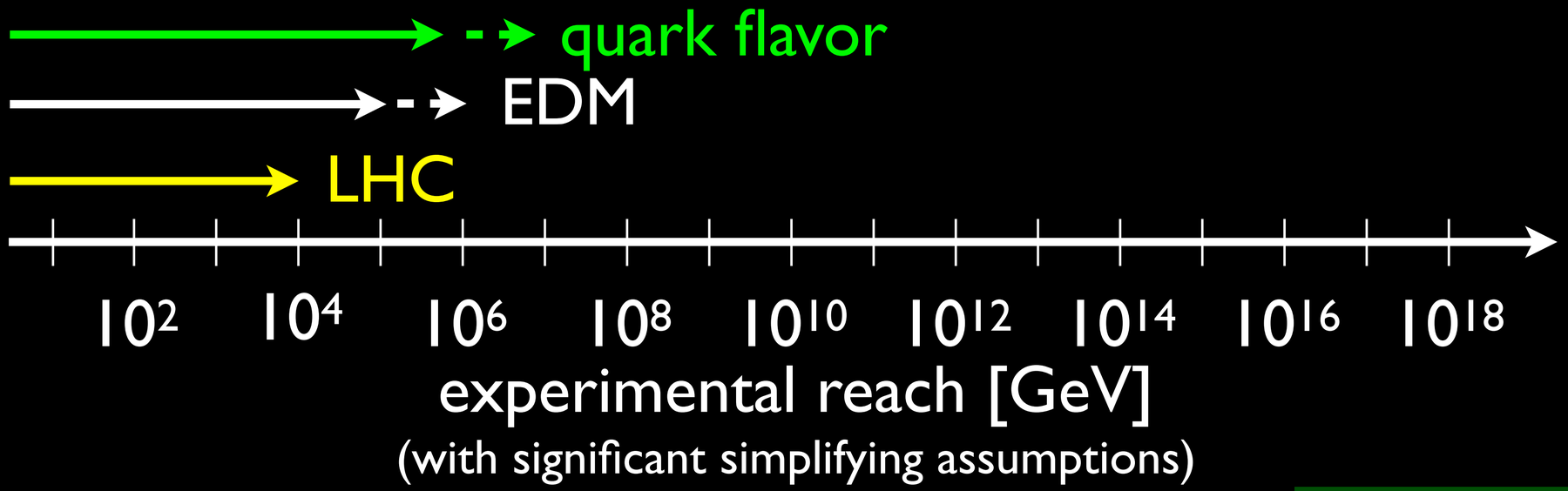

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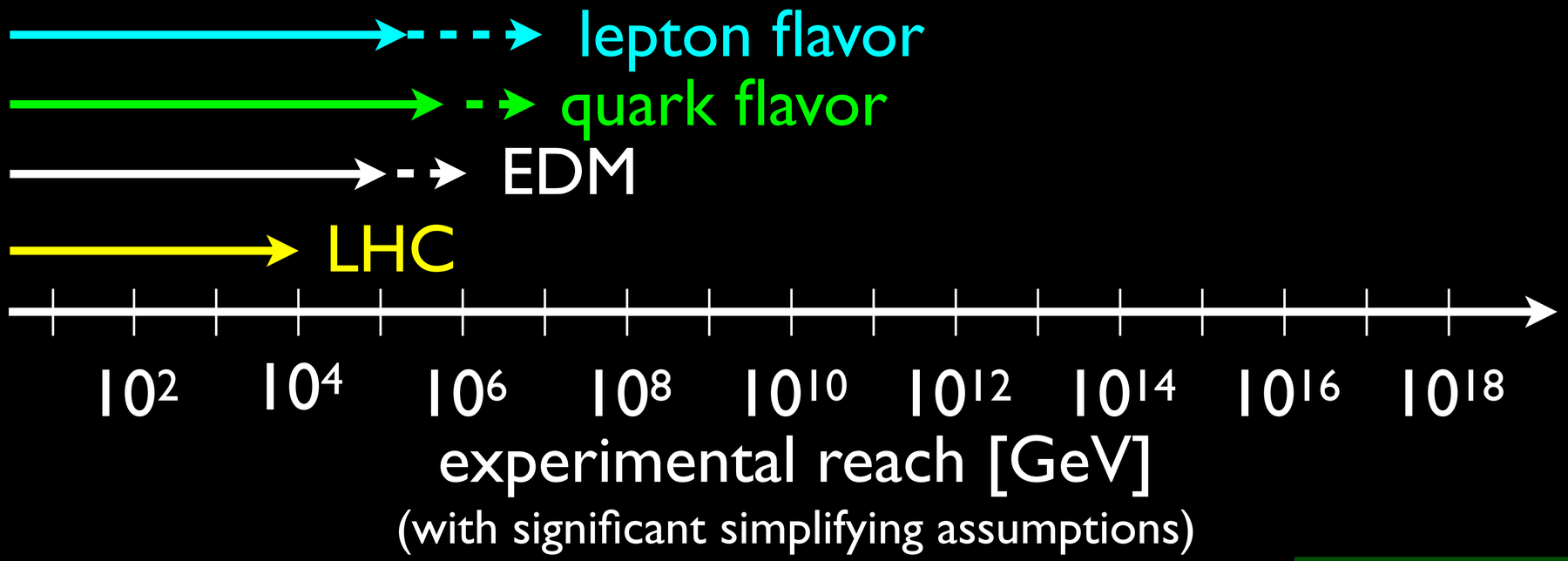

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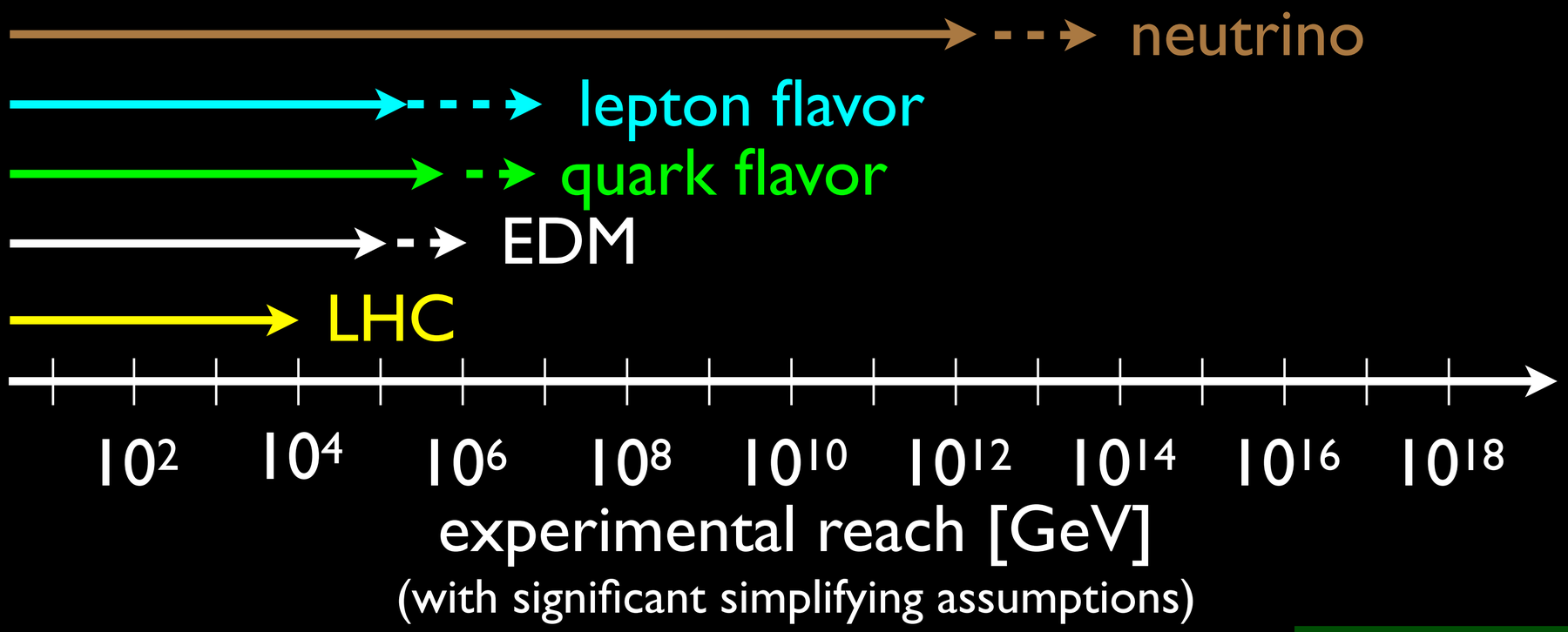

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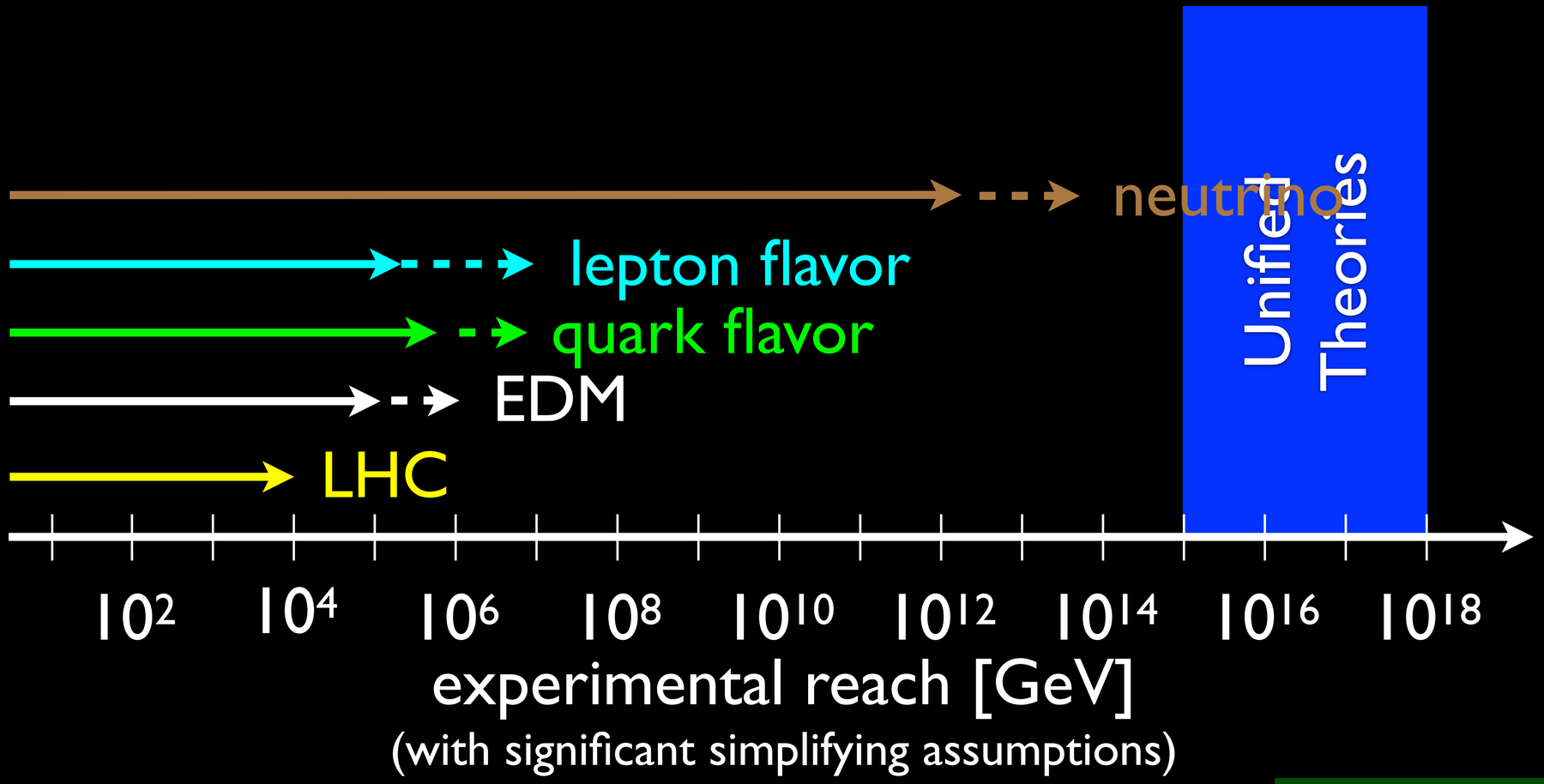

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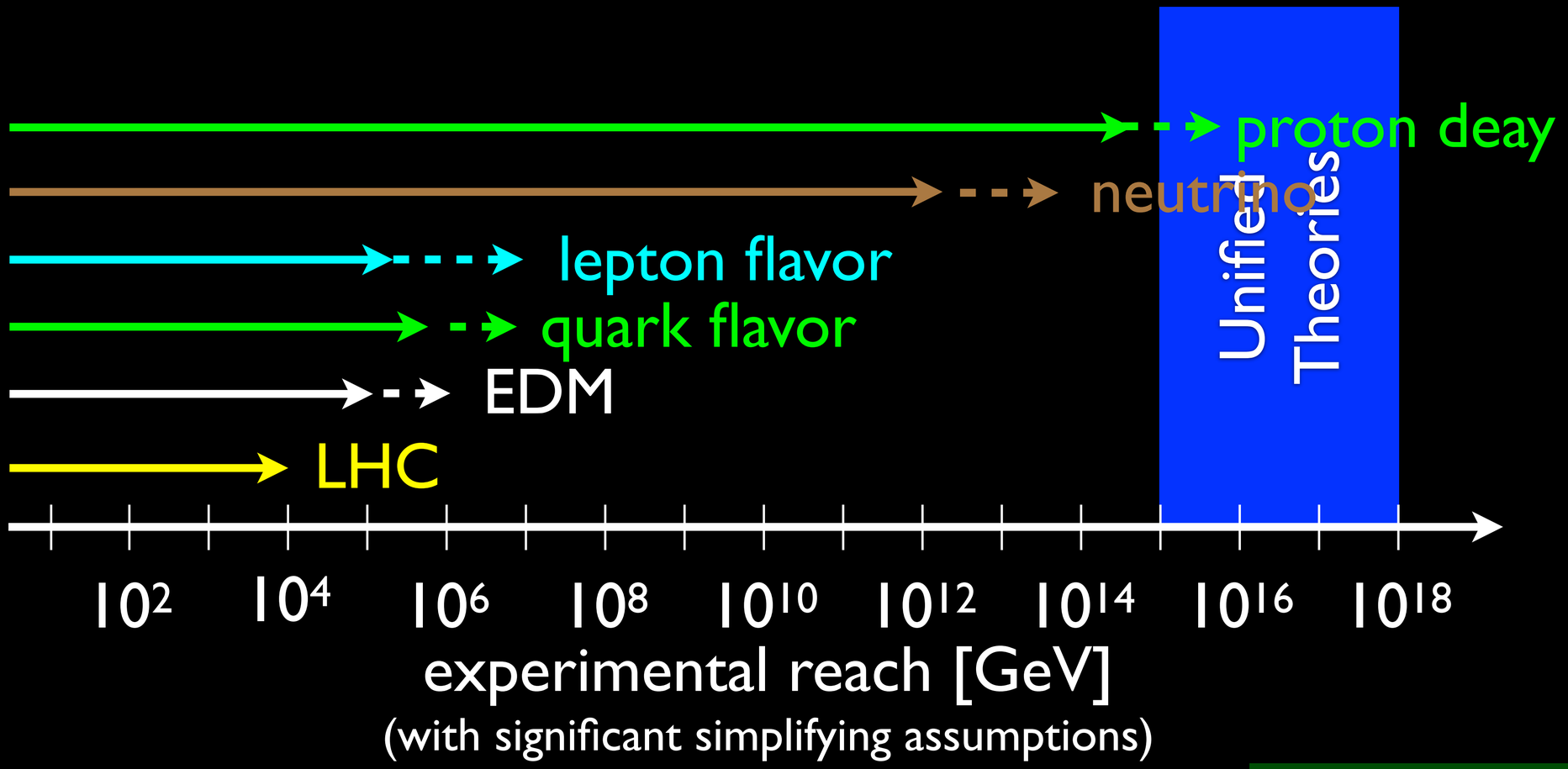

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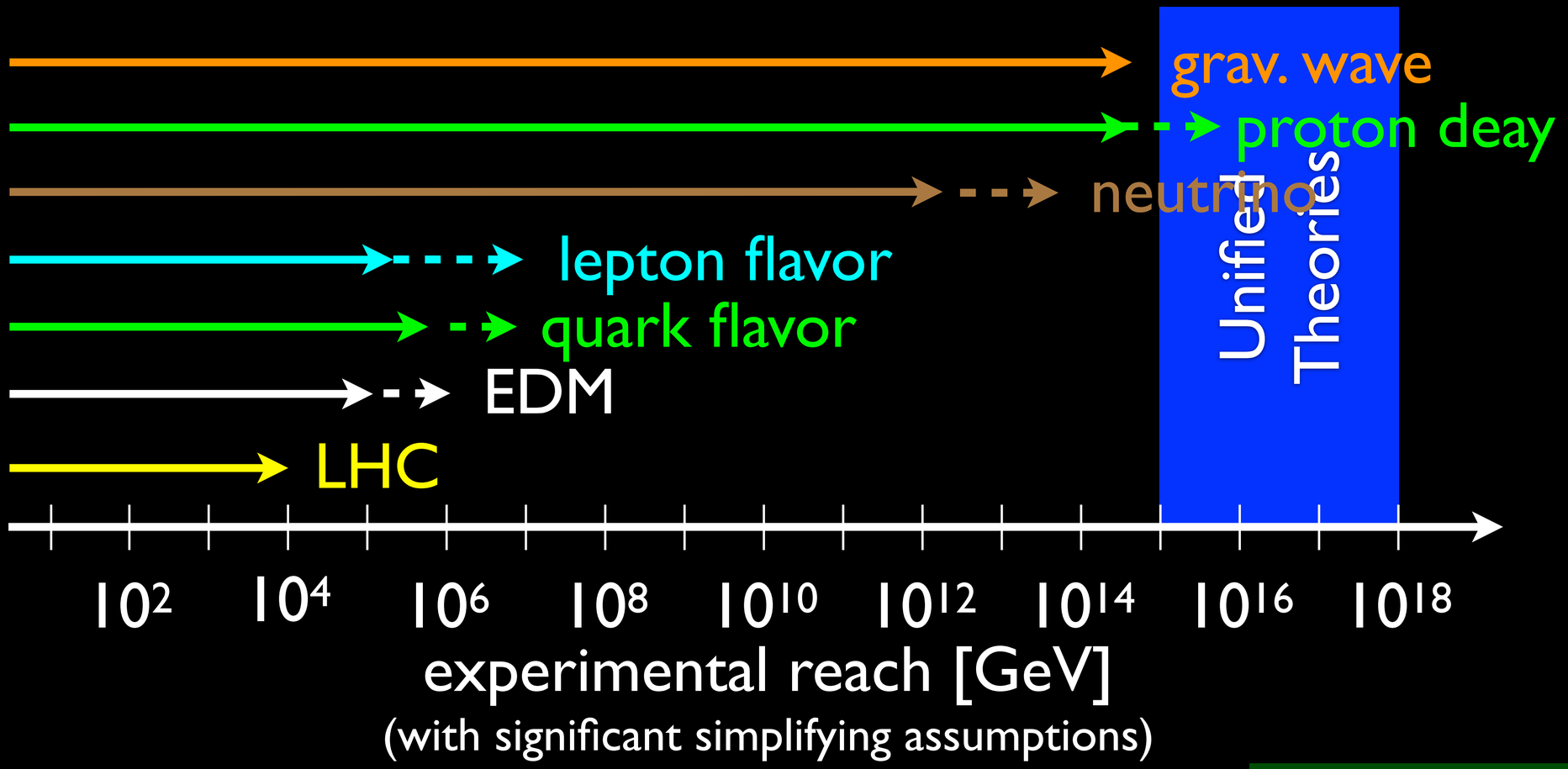


Caption Box

Our role

- Address *Big Problems* in our field
- Make use of all available wisdom/expertise
- exploit all available experimenta/observational data
- build a hypothesis (“*attractive*” in whatever definition)
- Make sure to derive testable prediction of the models
  - in particular, signatures not considered before
- but often fall into ideological debates

Caption Box

Guidelines

"The mathematical sciences particularly exhibit order, symmetry, and limitation; and these are the greatest forms of the beautiful."

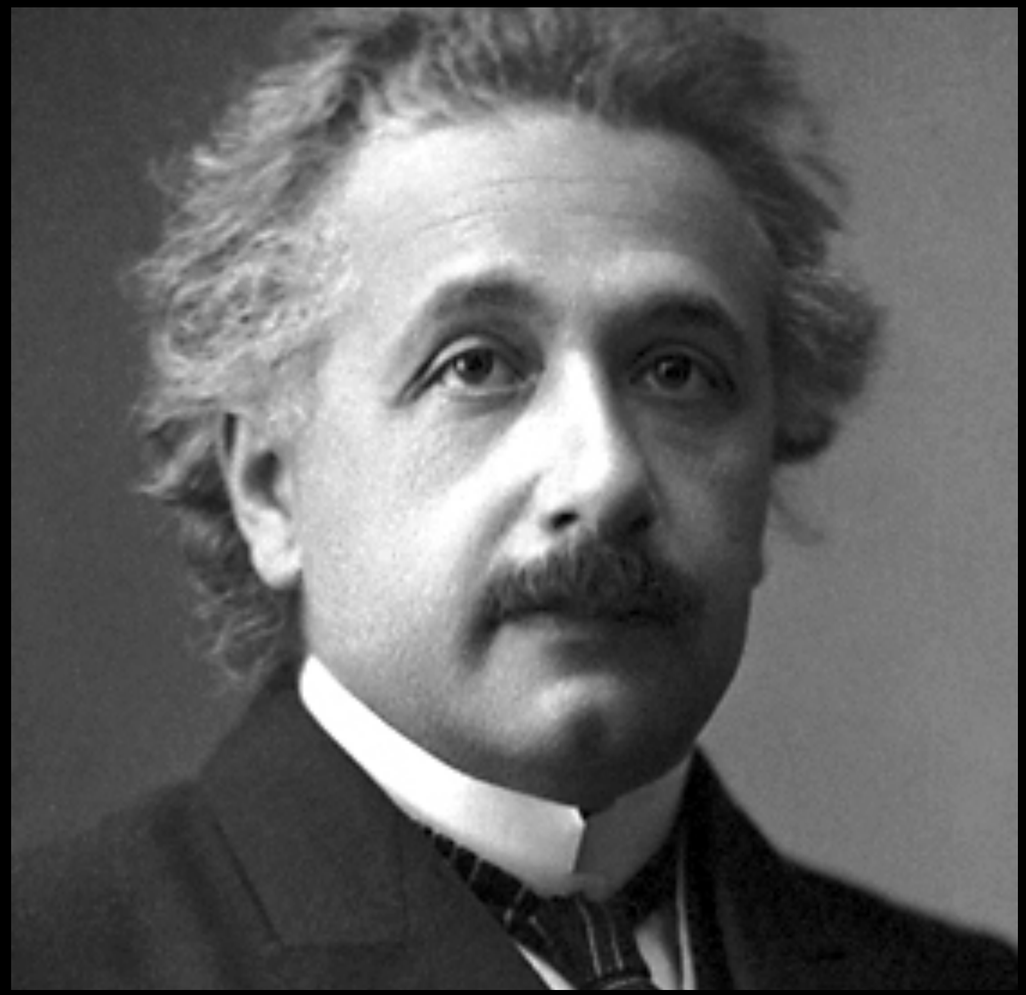
Aristotle

http://upload.wikimedia.org/wikipedia/commons/a

Caption Box

Guidelines

"I have deep faith that the principle of the universe will be beautiful and simple."



Albert Einstein

Caption Box

http://en.wikipedia.org/wiki/Albert_Einstein#mediav

Guidelines

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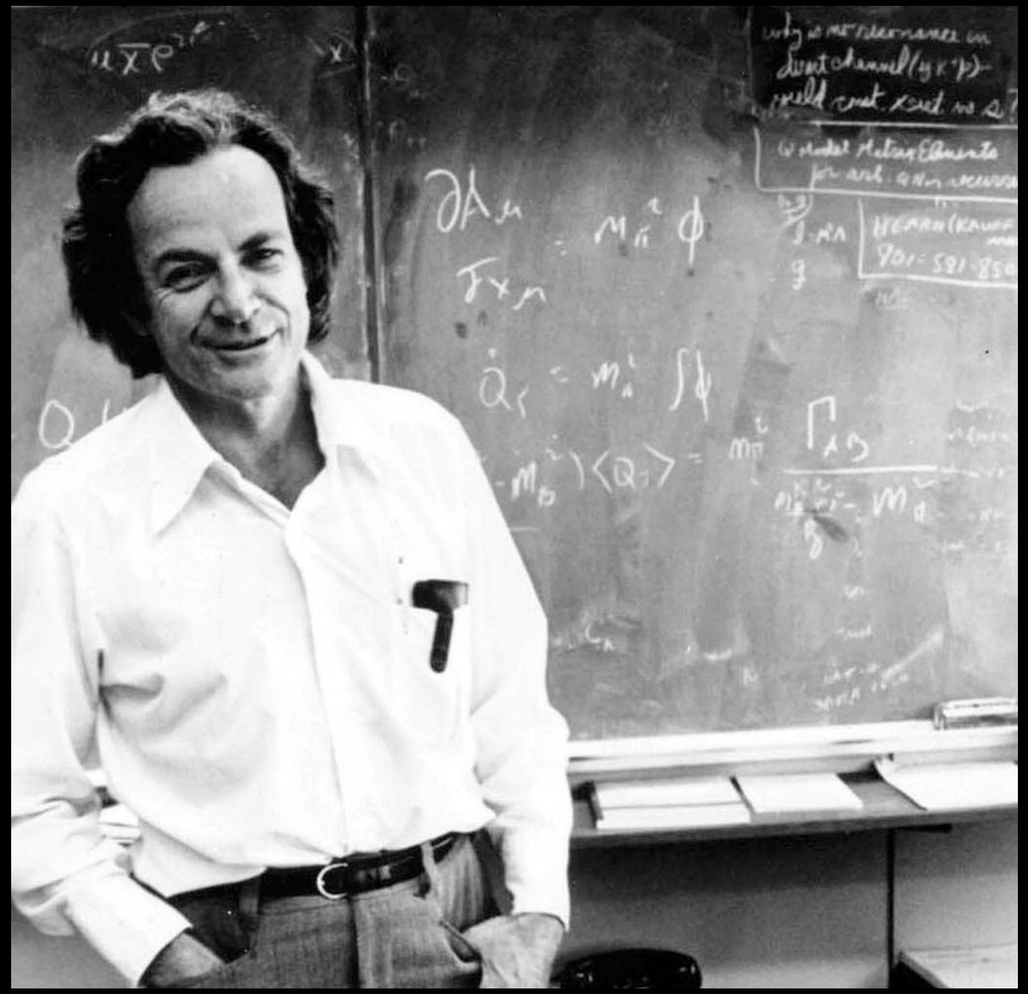
Nature has a great simplicity and therefore a great beauty.

Richard P. Feynman

meetville.com



Richard Feynman

http://meetville.com/quotes/tag/physics/page5

http://it.wikipedia.org/wiki/Richard_Feynman#medi

Caption Box

Guidelines

“Symmetry, as wide or as narrow as you may define it, is one idea by which man through the ages has tried to comprehend and create order, beauty, and perfection.”

Hermann Weyl

http://en.wikipedia.org/wiki/Hermann_Weyl#mediaviewer/File:Hermann

Caption Box

Guidelines

and woman

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Caption Box

Amalie Emmy Noether
1882-1935

Amalie Emmy Noether
1882-1935

Symmetry → Conservation law

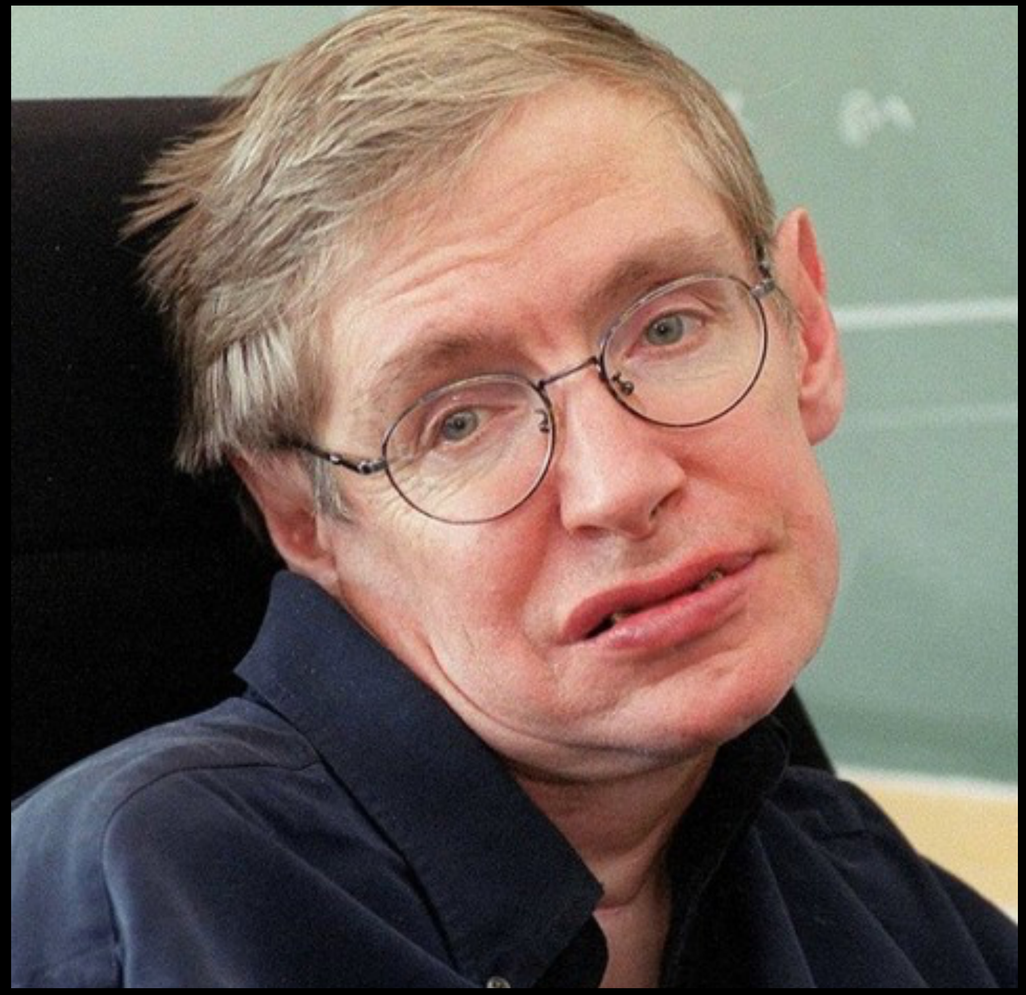
Amalie Emmy Noether
1882-1935

Symmetry → Conservation law

Symmetry ← Conserved charge

Guidelines

"Science is beautiful when it makes simple explanations of phenomena or connections between different observations. Examples include the double helix in biology and the fundamental equations of physics."



Stephen Hawking

http://www.brucebergerrecords.com/category/stephen-hawking/

Guidelines

What is especially striking and **remarkable** is that in fundamental **physics** a beautiful or elegant **theory** is more likely to be **right** than a **theory** that is inelegant.

Murray Gell-Mann

meetville.com

Murray Gell-Mann

http://www.nobelprize.org/nobel_prizes/physics/laureates/1969/gell-mann-bio.html

Guidelines

“For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation.”

Thomas Gold

Caption Box

Guidelines

“This is often the way it is in physics - our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world. Even worse, there often seems to be a general agreement that certain phenomena are just not fit subjects for respectable theoretical and experimental effort.”

Steven Weinberg

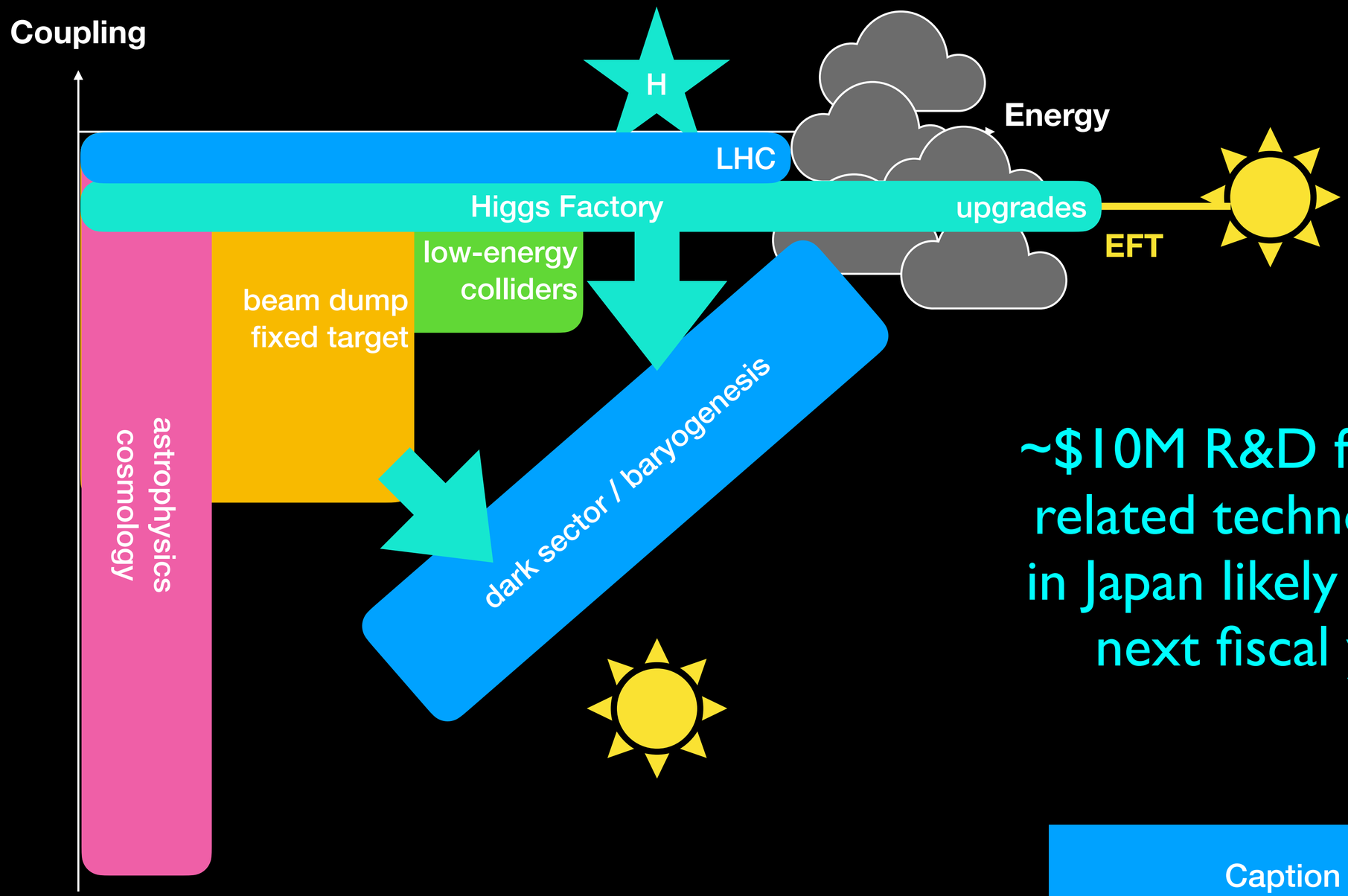
Caption Box

What we thrive

- Rely on most updated data and make forecasts for
  - energy frontier, neutrino frontier, cosmic frontier, rare processes and precision frontier
- use advancements in our understanding of QFT, EFT, experimental tools
  - theory frontier, computational frontier, instrumentation frontier, accelerator frontier, underground facilities and infrastructure frontier
- include everybody interested
  - community engagement

Caption Box

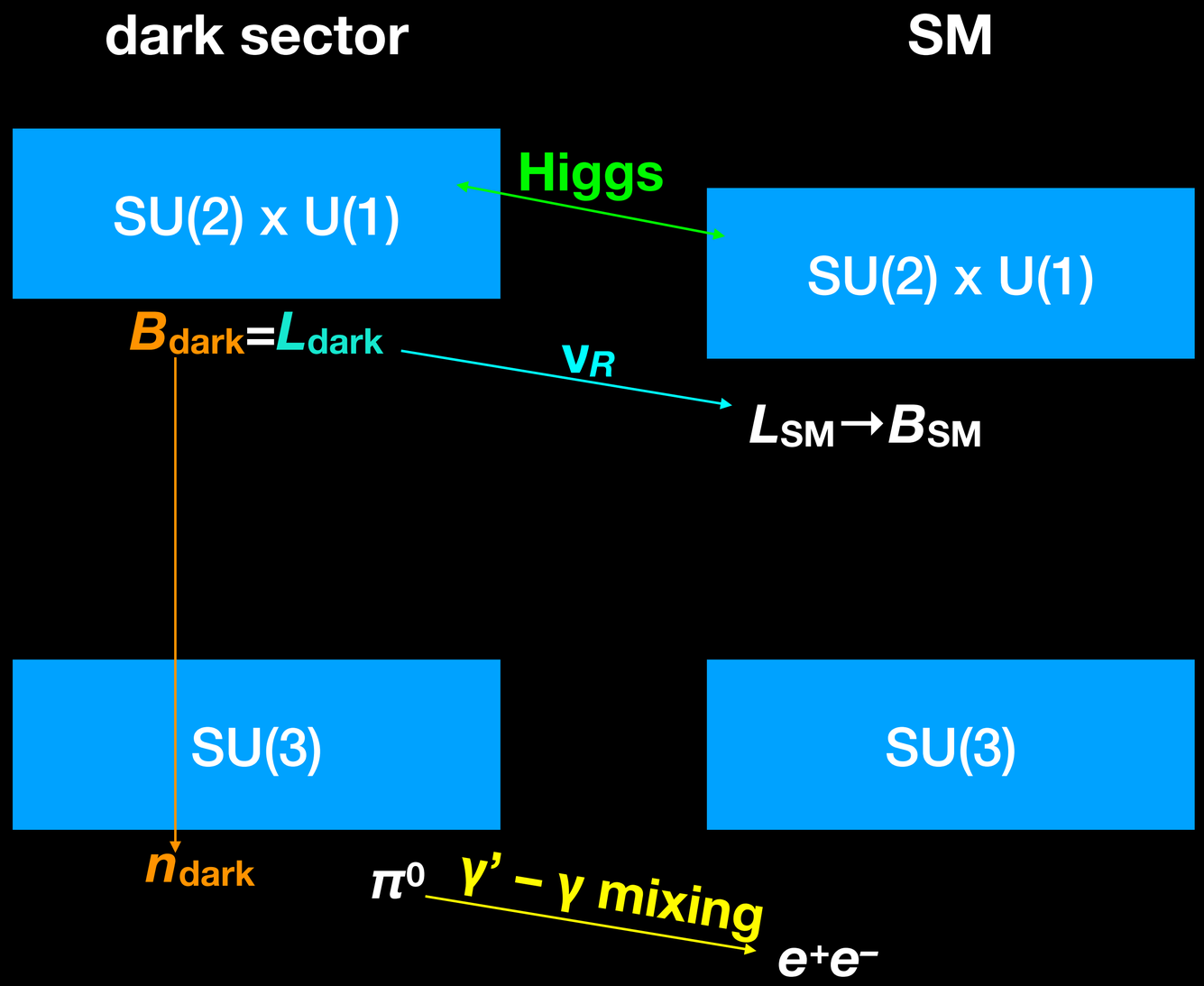
What shall we do?



~$10M R&D for ILC-related technologies in Japan likely for the next fiscal year

Caption Box

baryogengesis + DM



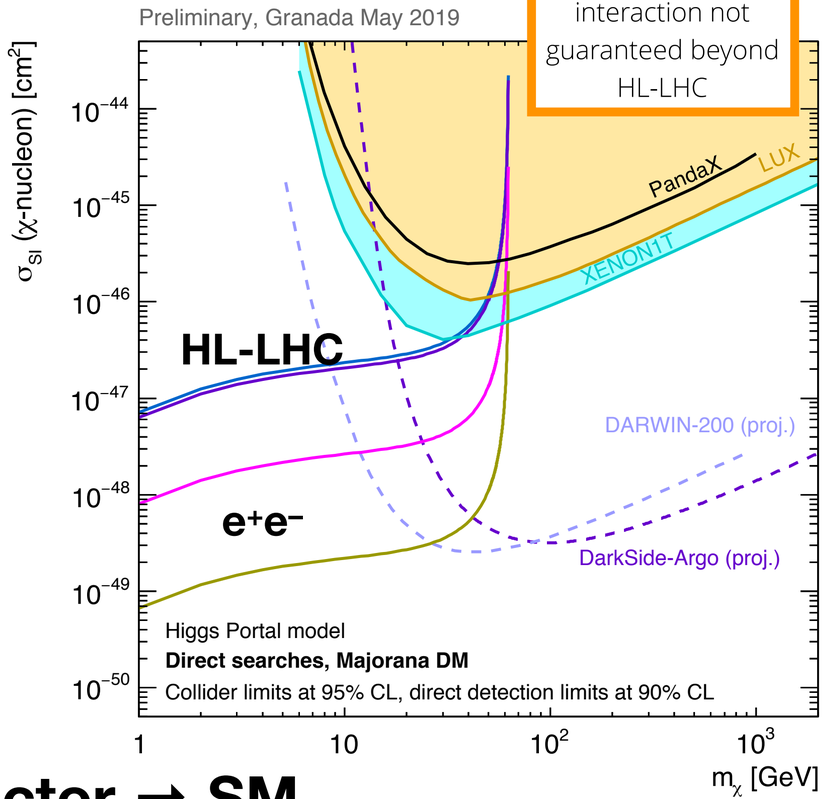
Dark baryon: ~1.5 GeV (or ~60 GeV)

Caption Box

direct detection limits

Higgs decay to dark matter

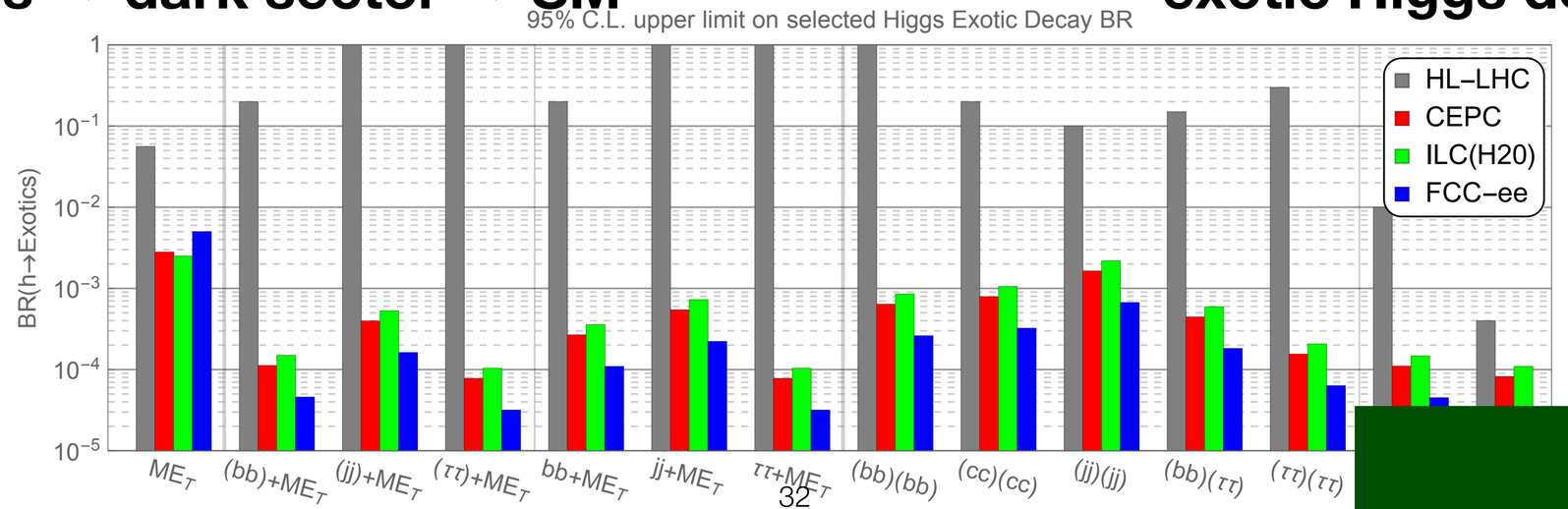
x10 HL-LHC



Higgs → dark sector → SM

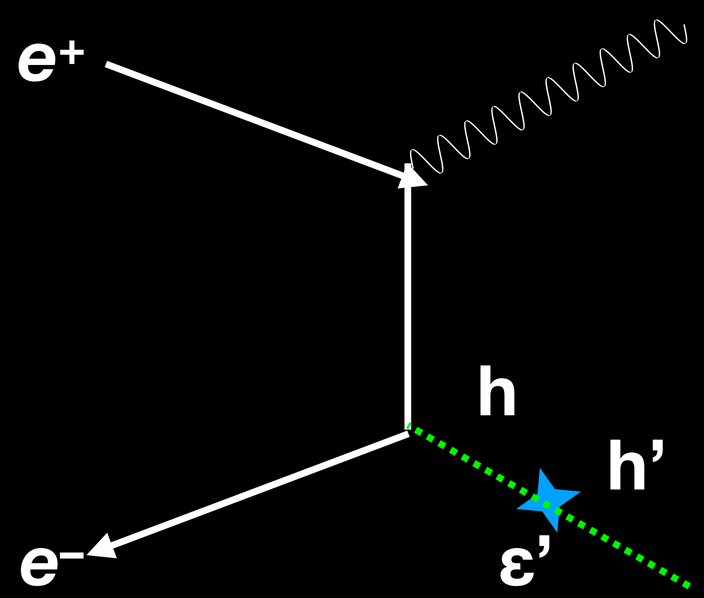
x1000–10000 HL-LHC

exotic Higgs decays



Caption Box

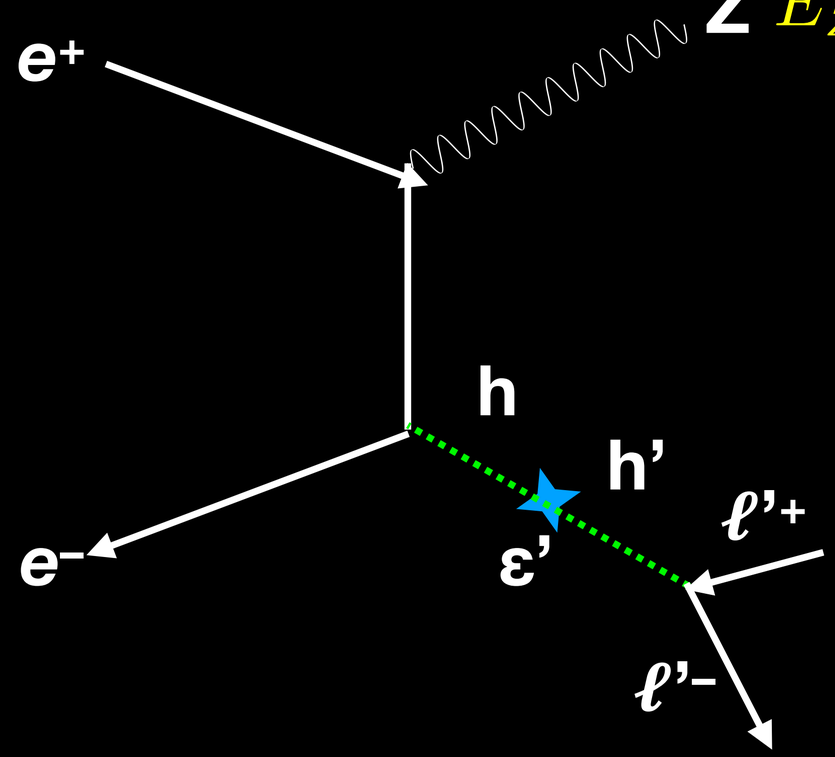
Higgs portal



$$E_Z = \frac{\sqrt{s}}{2}\left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s}\right)$$

Caption Box

Higgs portal



Caption Box

Higgs portal

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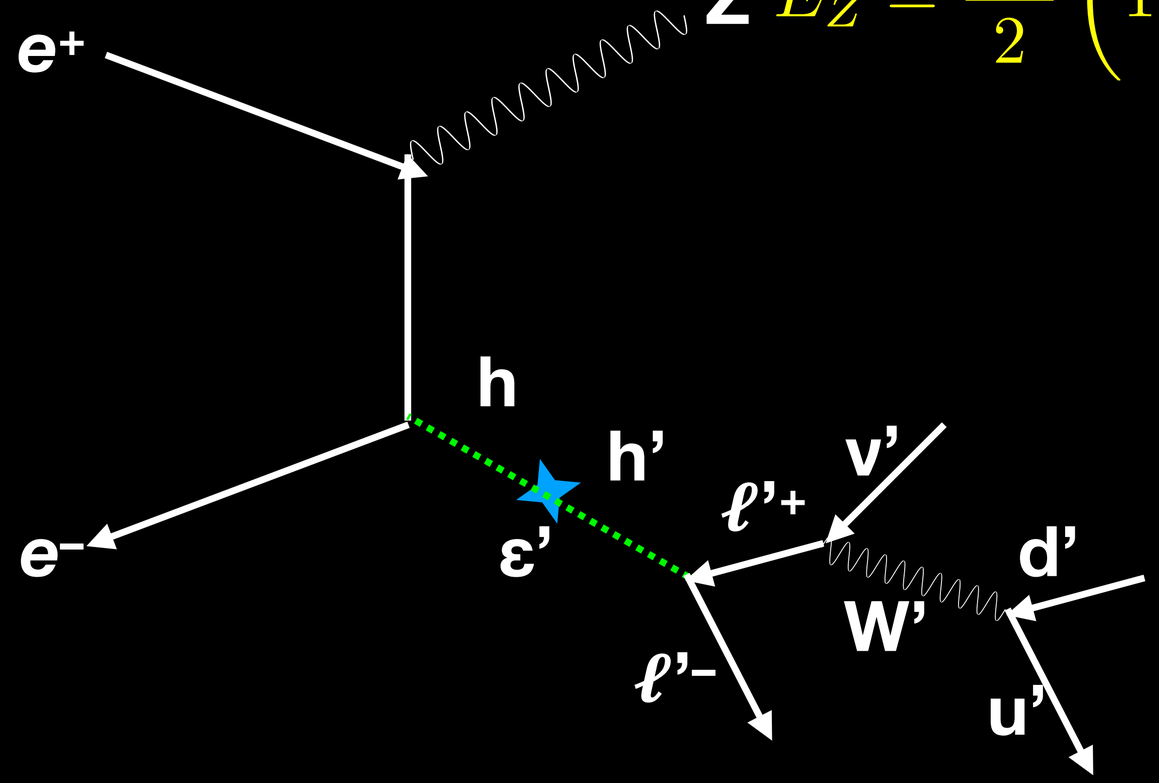

Caption Box

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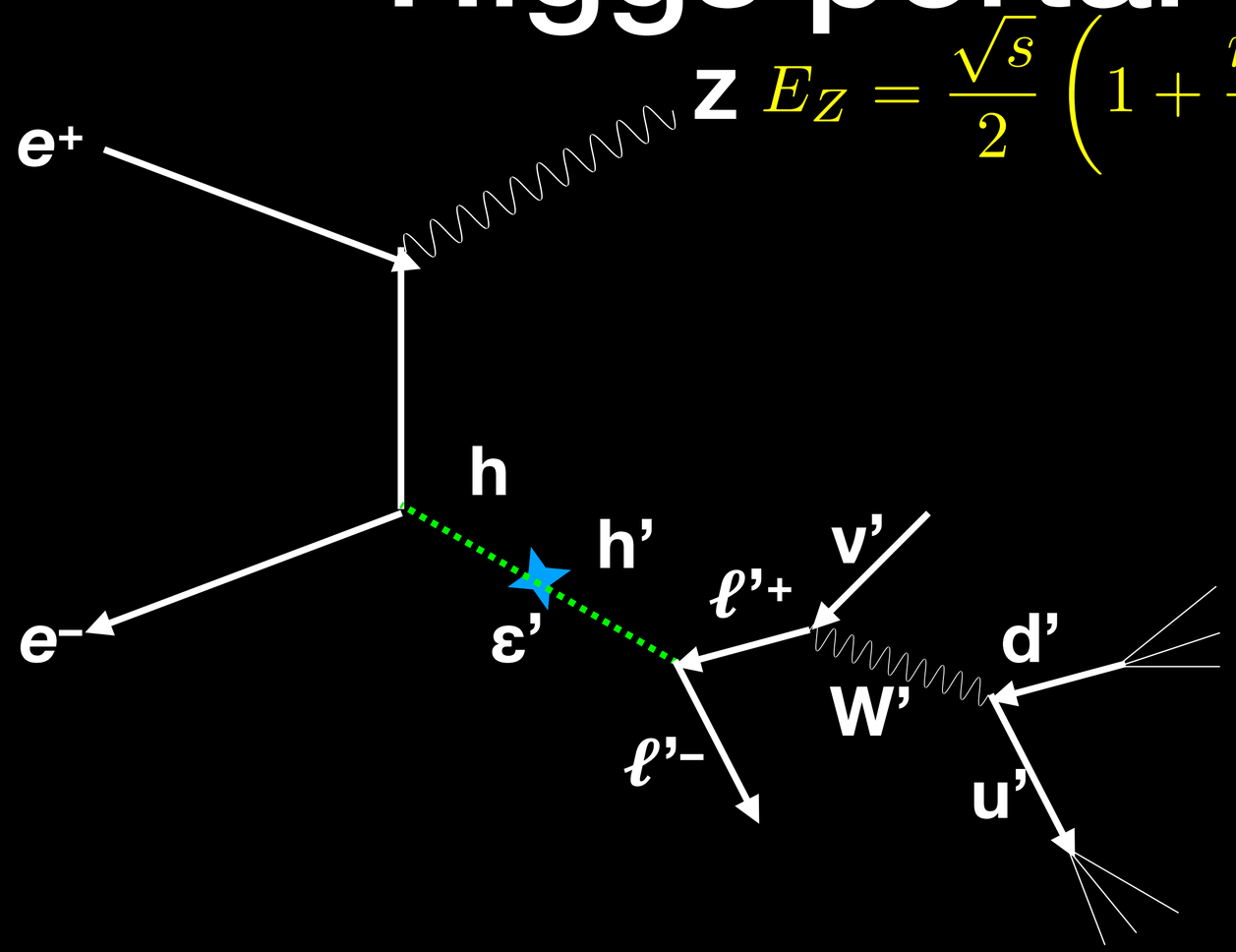
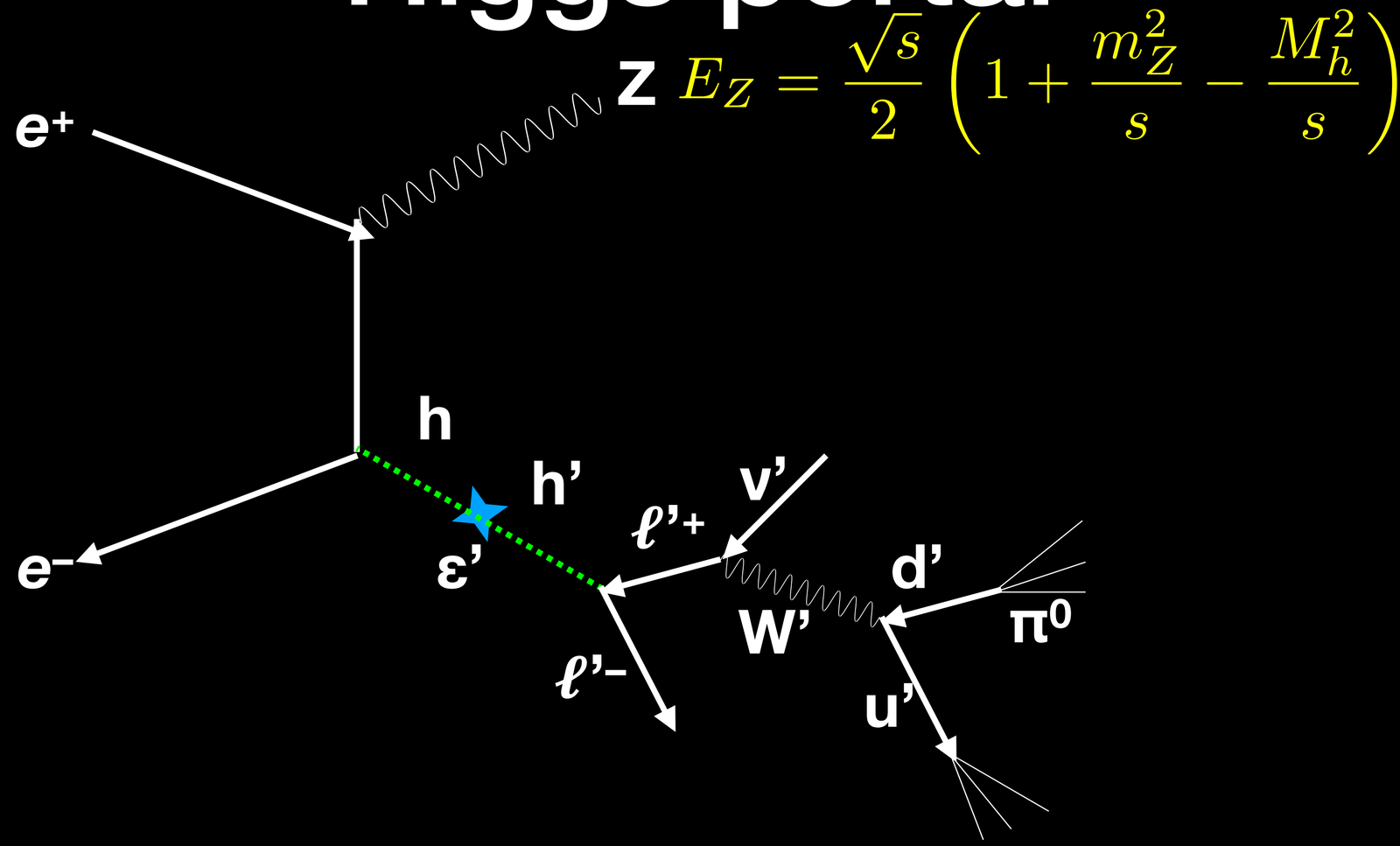


Caption Box

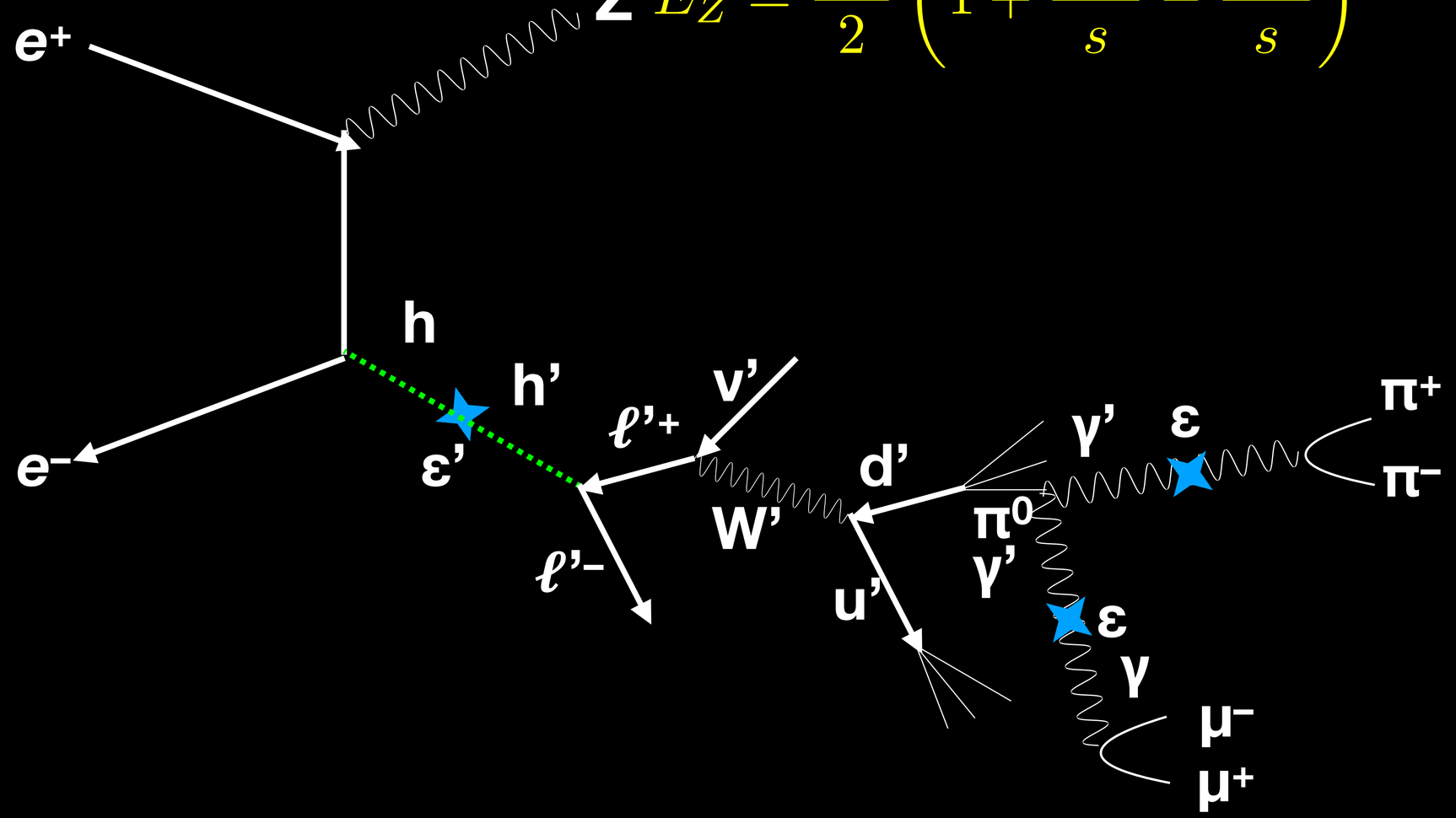
Higgs portal



Caption Box

Higgs portal

z $E_Z = \frac{\sqrt{s}}{2}\left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s}\right)$



Caption Box

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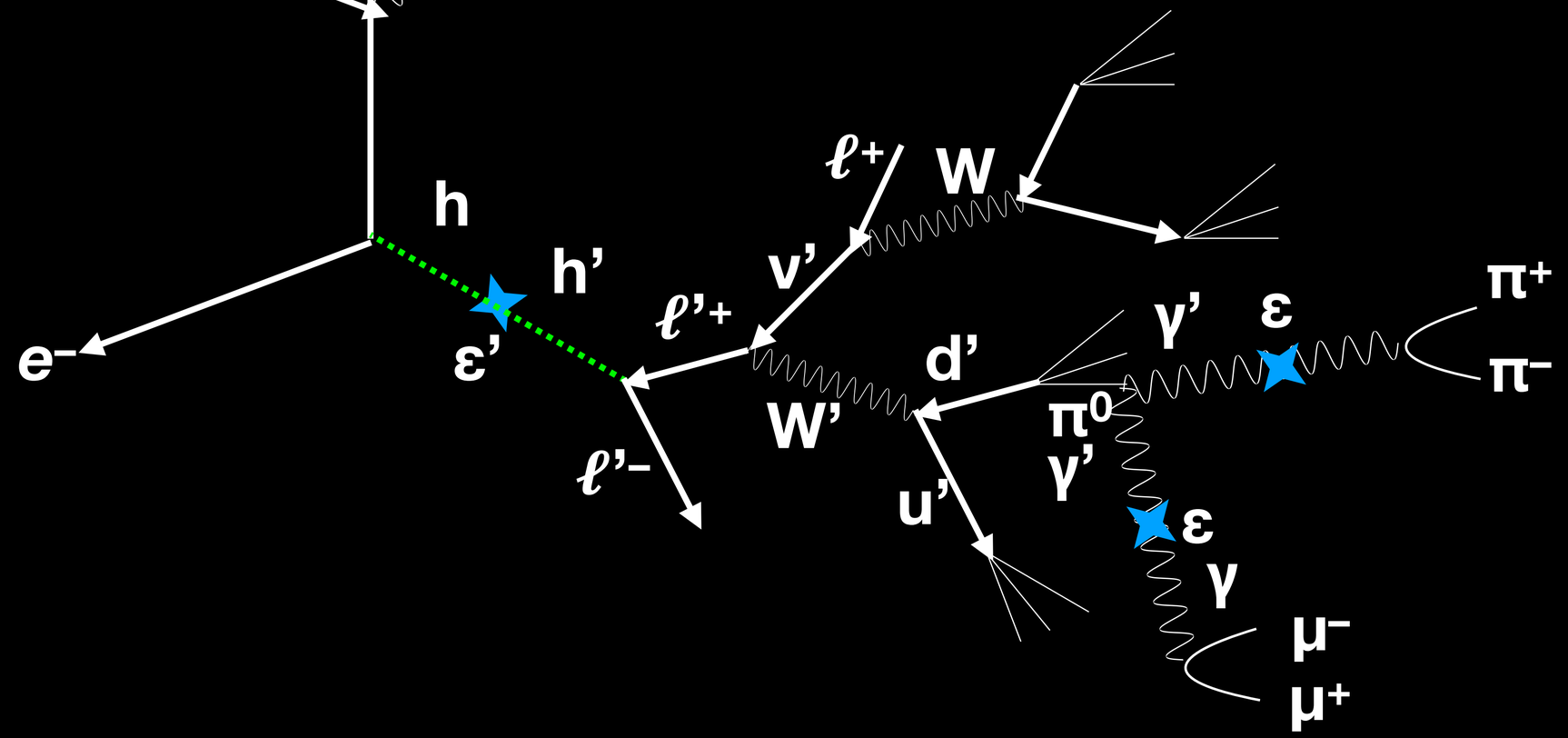


Caption Box

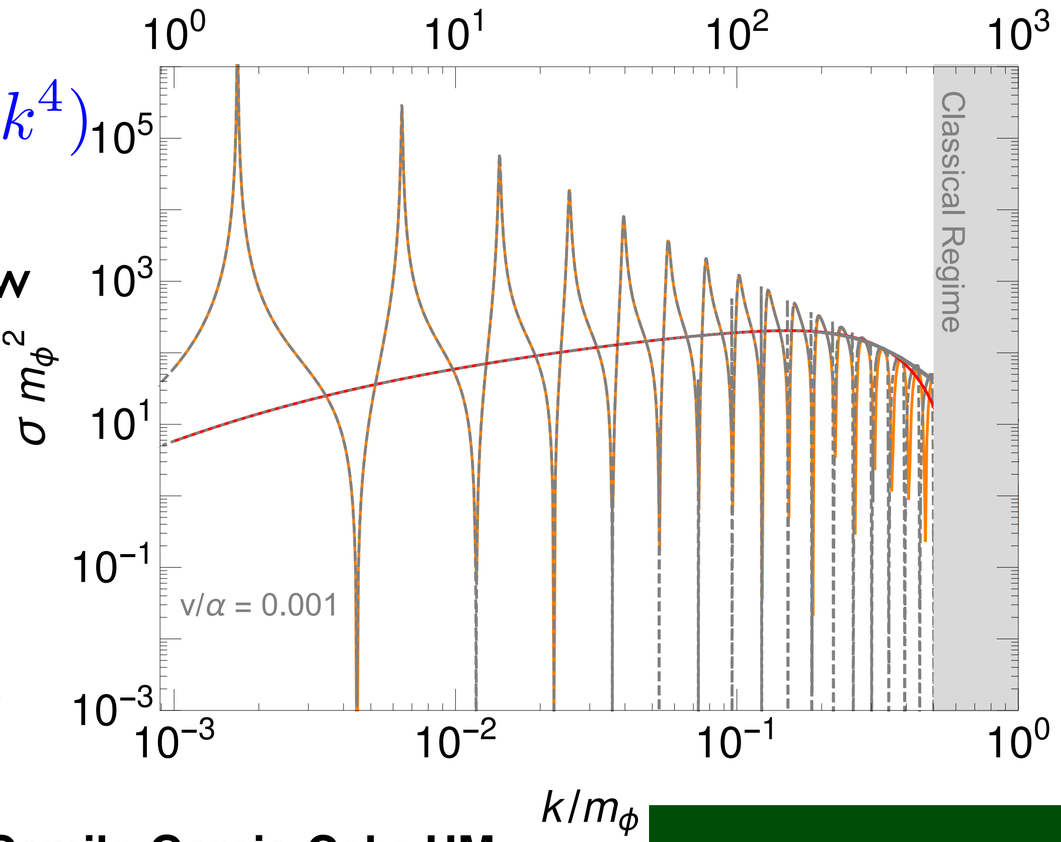
Unified description of SIDM

- Hans Bethe: effective range theory

$$k \cot \delta = -\frac{1}{a} + \frac{1}{2} r_e k^2 + O(k^4)$$

- only two parameters to describe scattering at low velocities
- fully unitary and non-perturbative
- ideal for simulations and phenomenology!
- resonance, bound states, virtual states

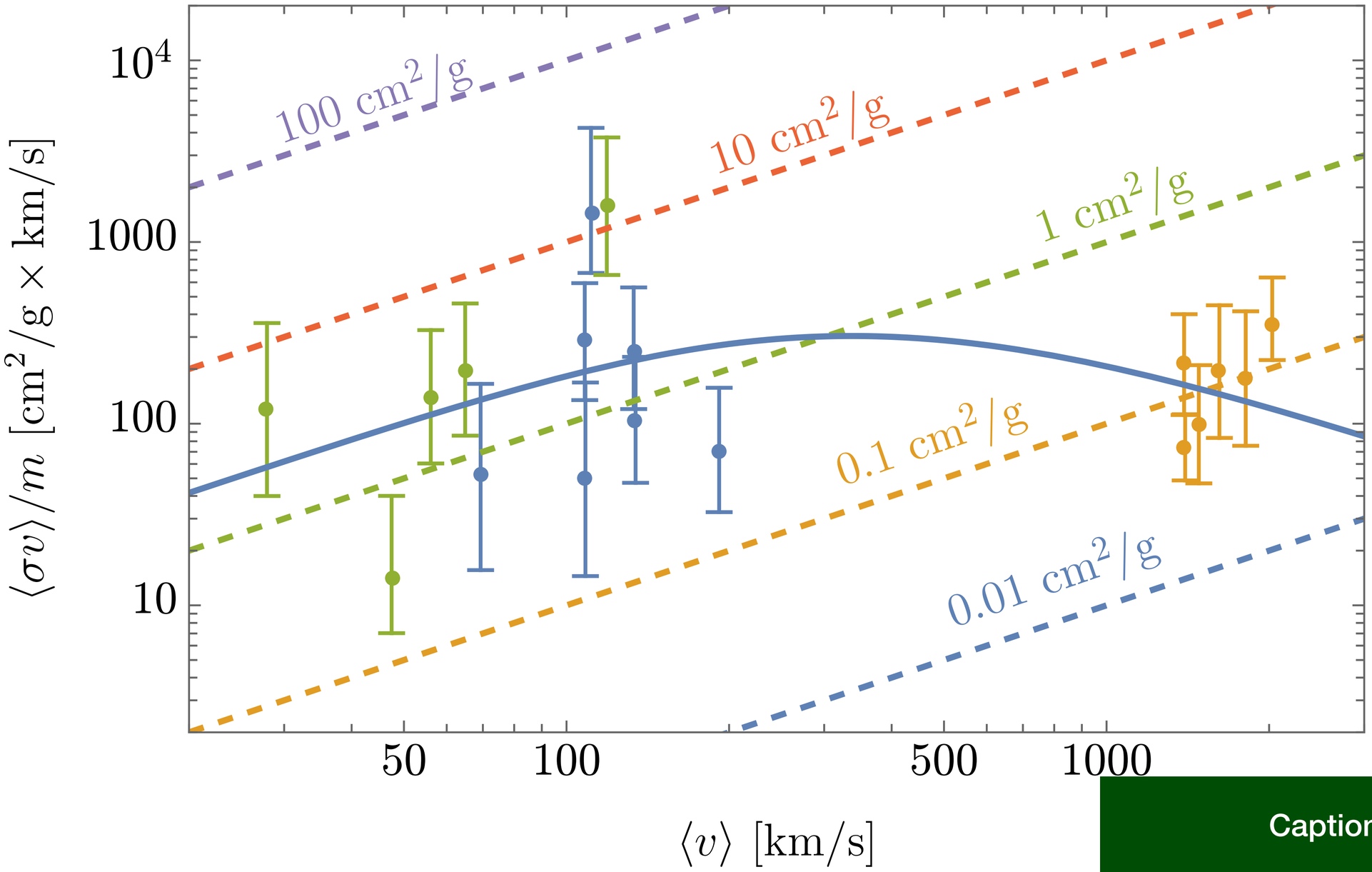
$$V = -\alpha \frac{e^{-m_\phi r}}{r}$$



Xiaoyong Chu, Camilo Garcia-Cely, HM, arXiv:1908.06067, *JCAP* 06 (2020) 043

Caption Box

best fit



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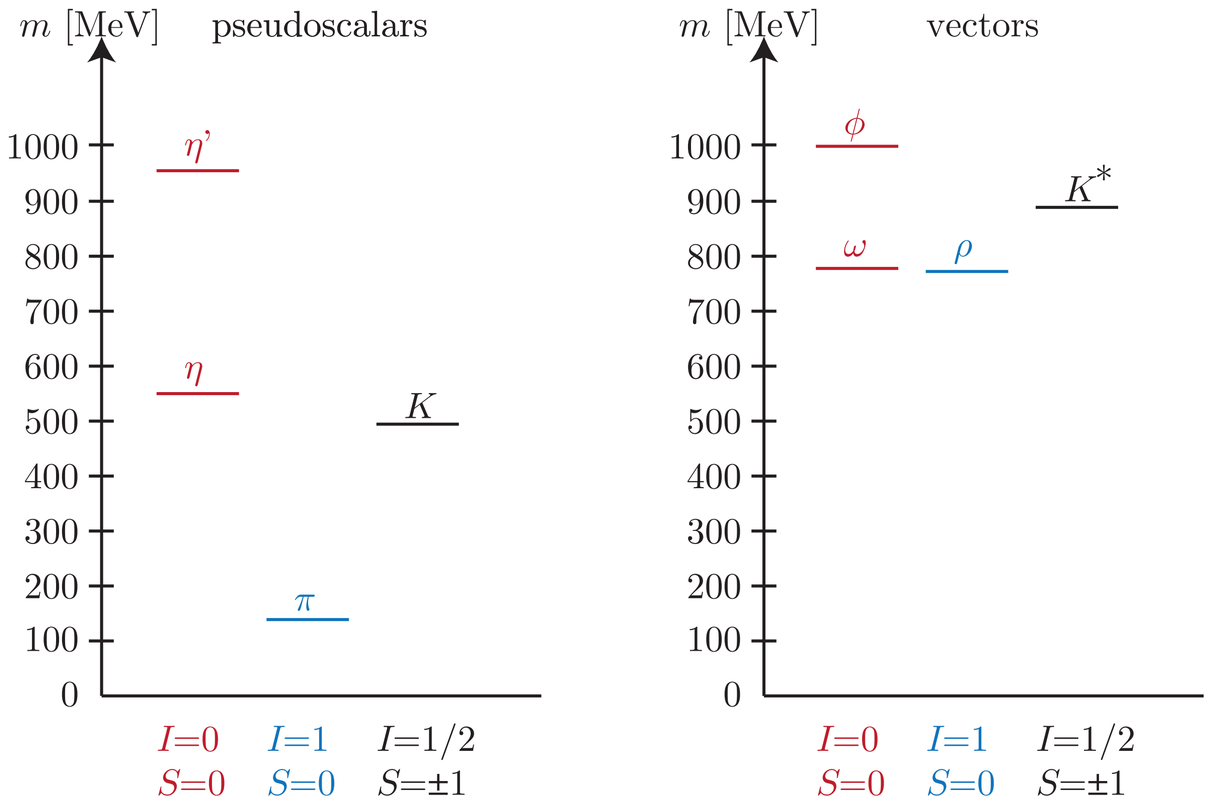
m [MeV]
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900
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700
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500
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300
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100
0
η'
η
K
π
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S=0
I=1
S=0
I=1/2
S=±1
m [MeV]
vectors
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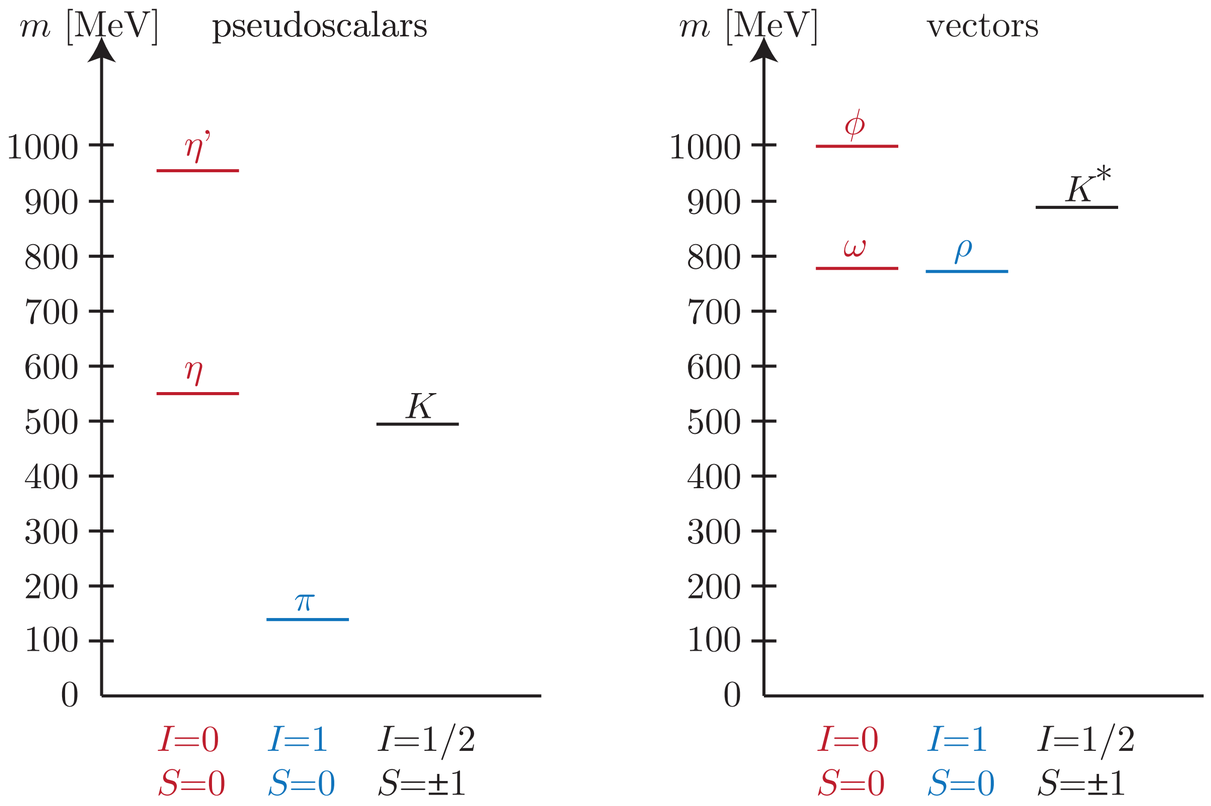
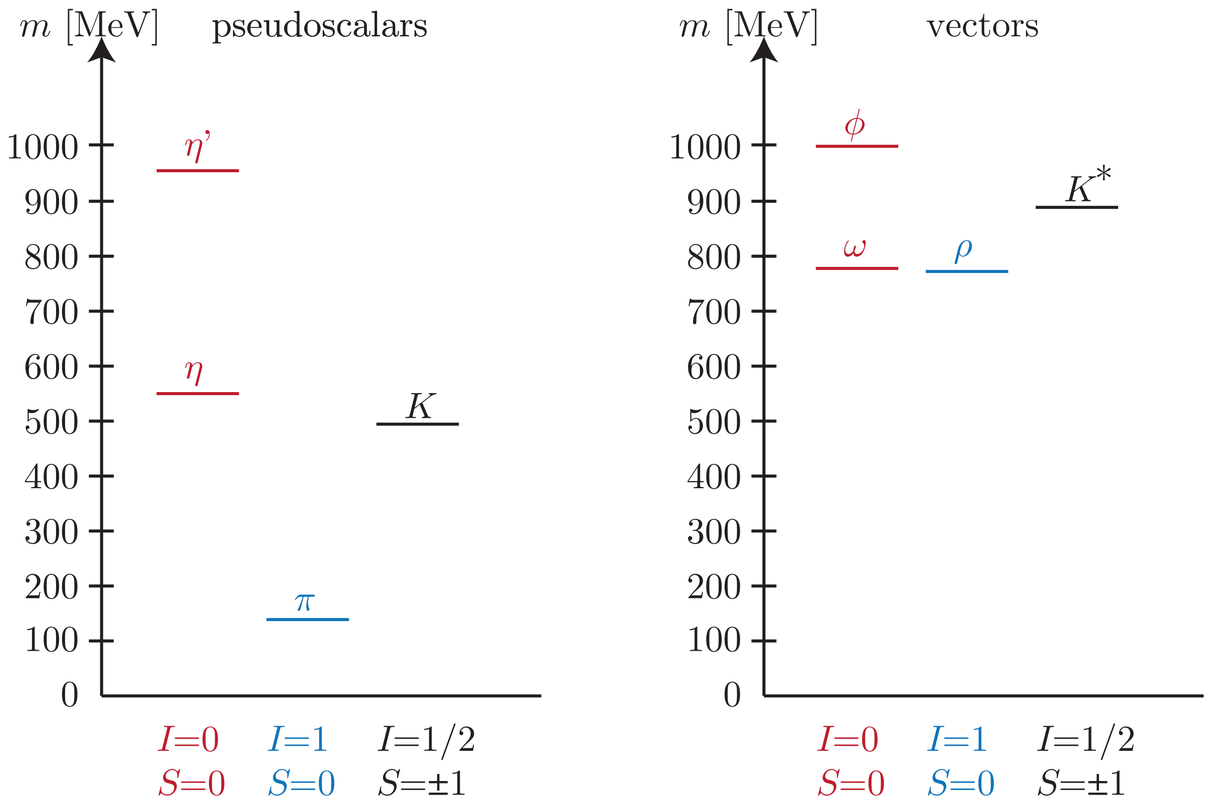


Gell-Mann–Okubo relation

Caption Box

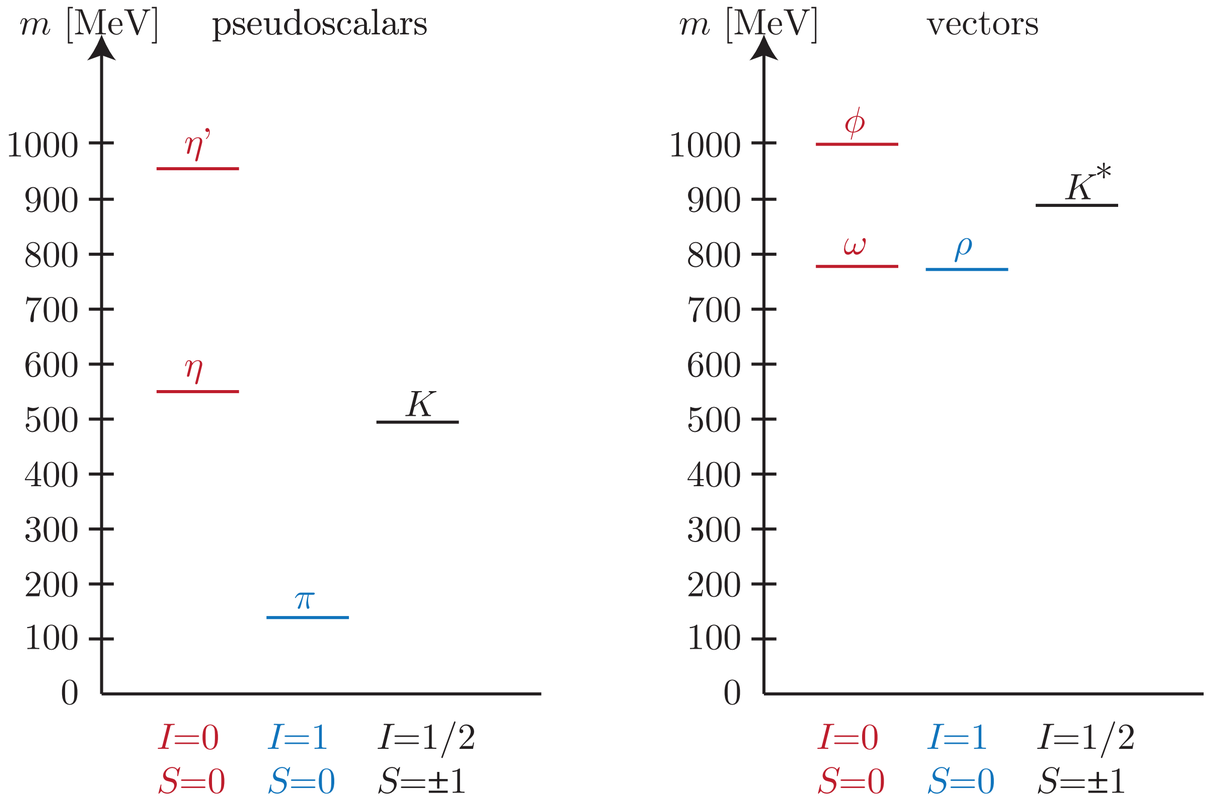


Gell-Mann–Okubo relation

K: $4 \times 0.496^2 = 0.984$ GeV^2

π_0, η: $0.140^2 + 3 \times 0.550^2 = 0.927$ GeV^2

Caption Box



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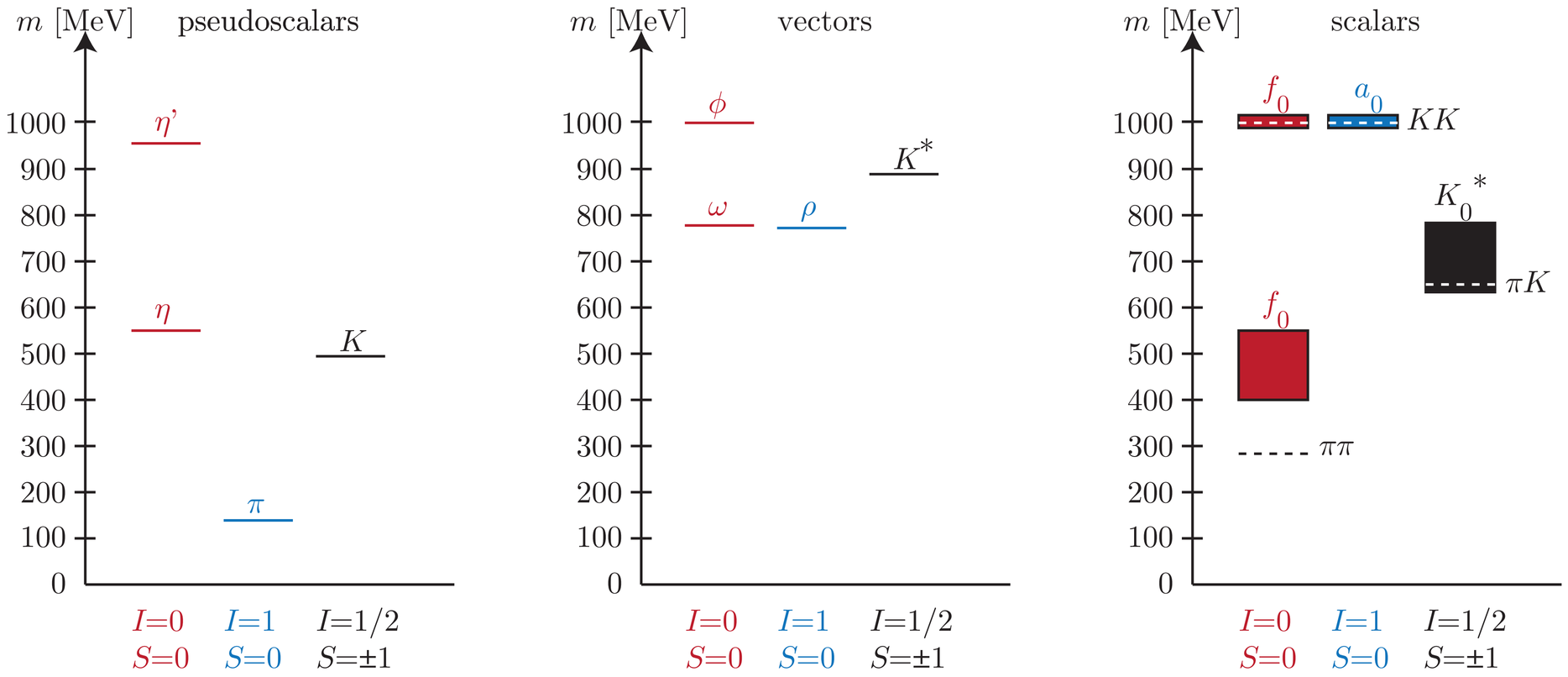
K^*: $4 \times 0.890^2 = 3.168$ GeV^2

ρ, $\omega\phi$: $0.780^2 + (0.780^2 + 2 \times 1.00^2) = 3.217$ GeV^2

Caption Box



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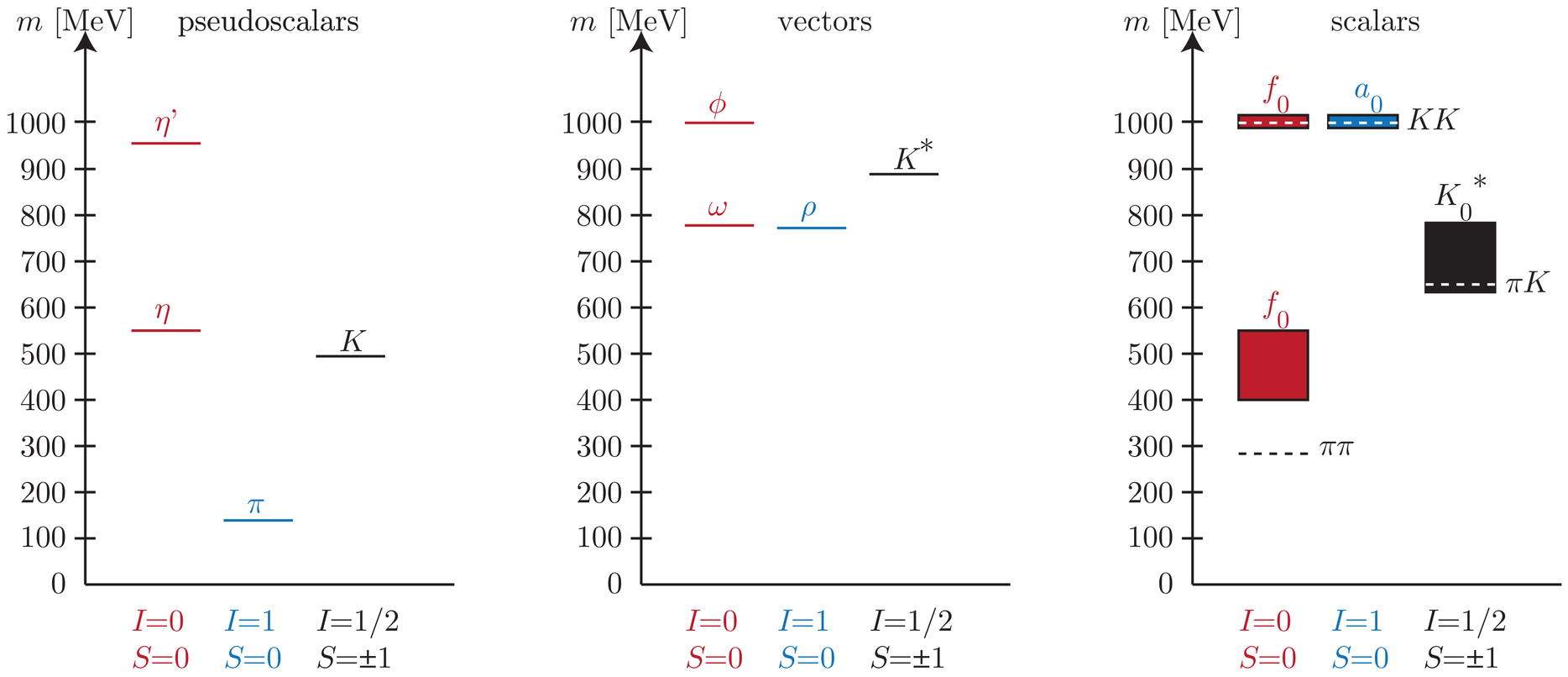

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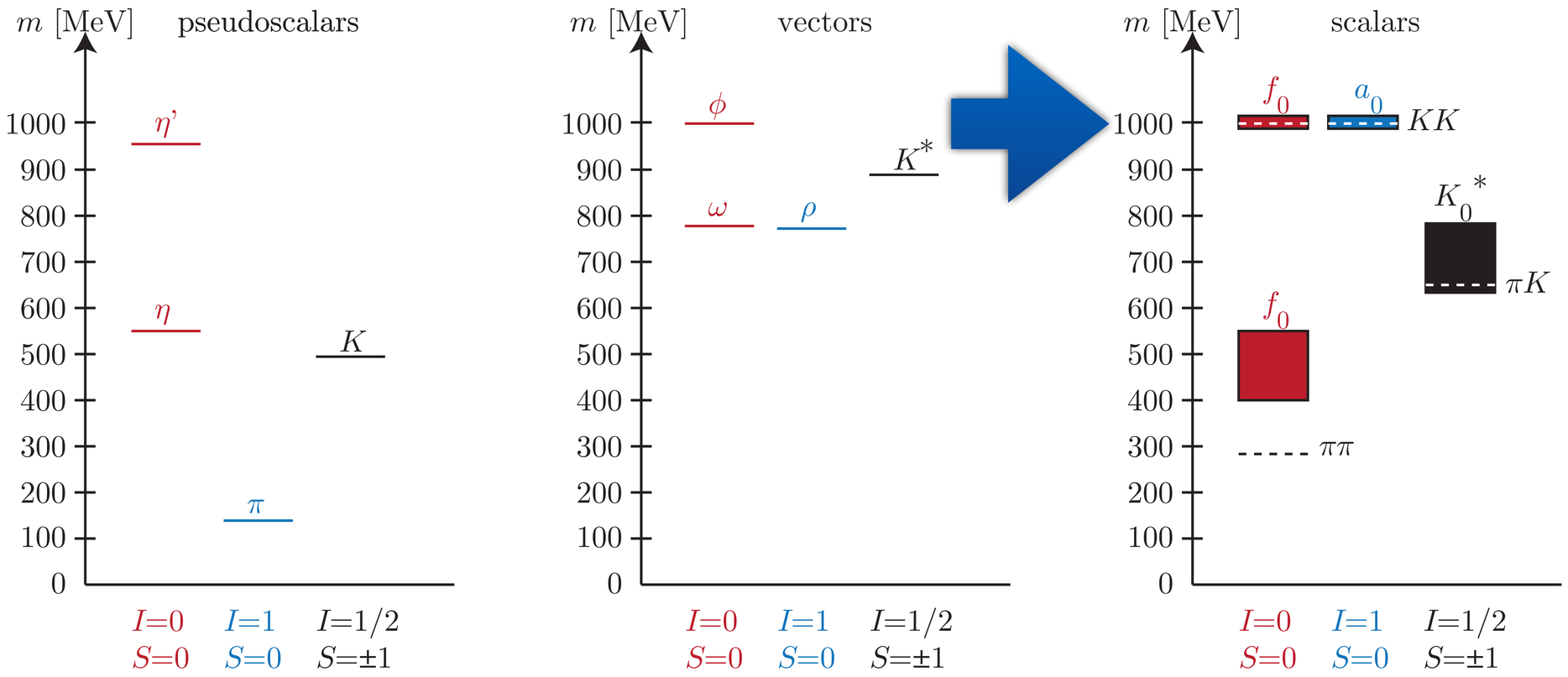
Dan Kondo, Robert McGehee, Tom Melia, HM, arXiv:2205.08088



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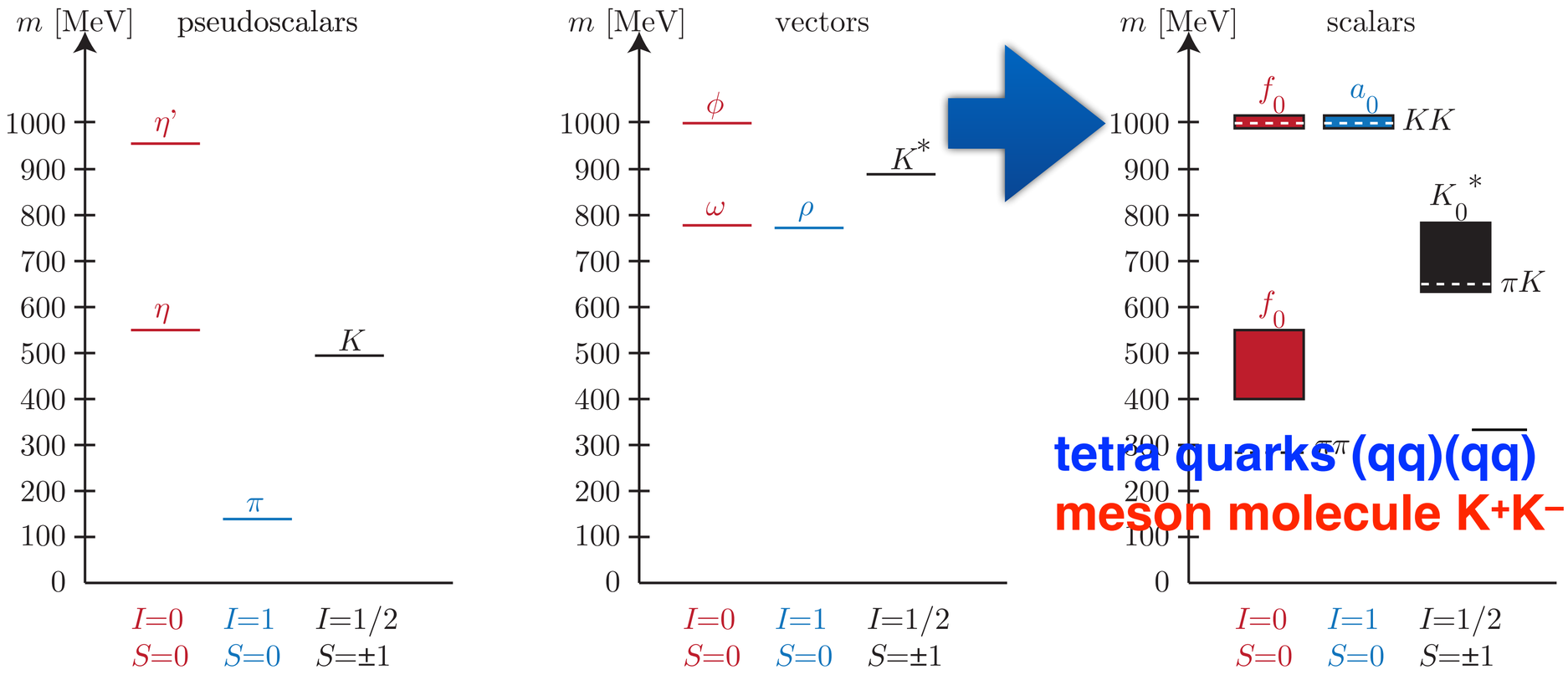

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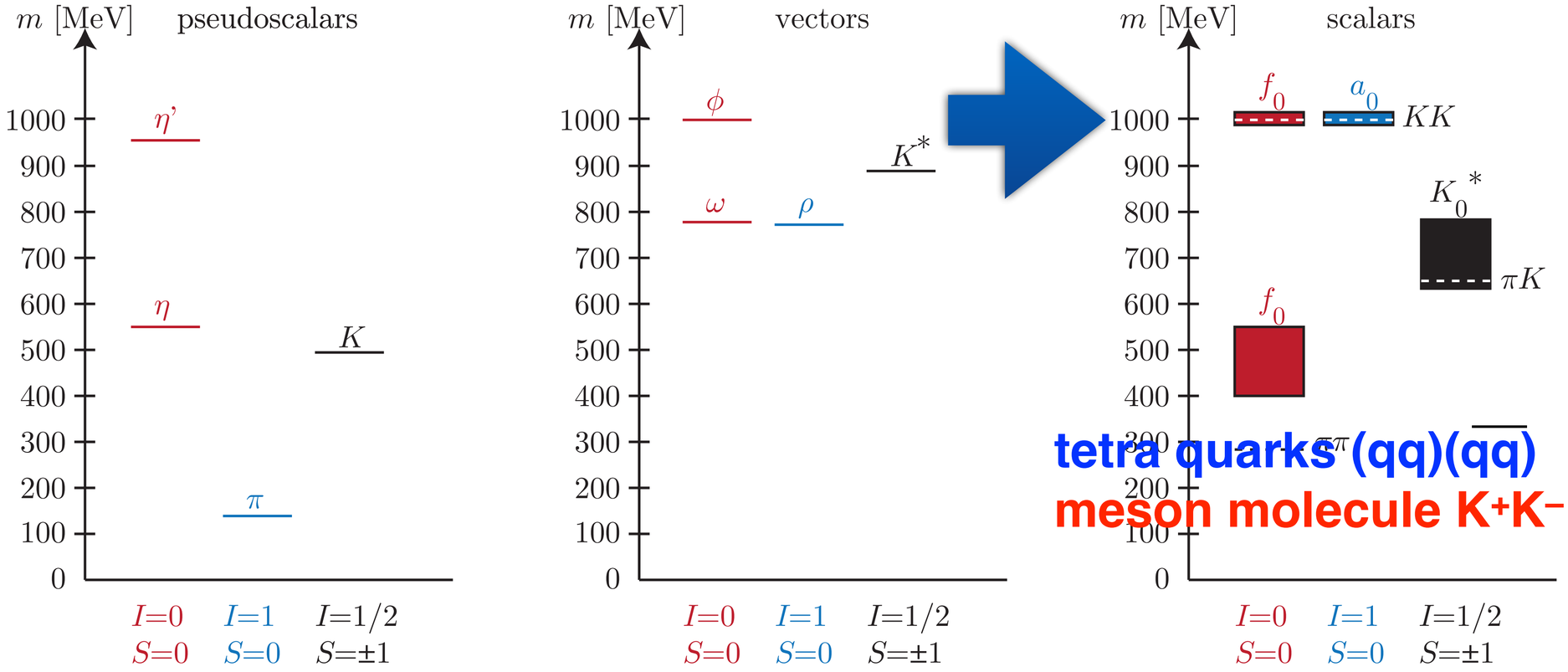
Dan Kondo, Robert McGehee, Tom Melia, HM, arXiv:2205.08088

revenge of sigmas



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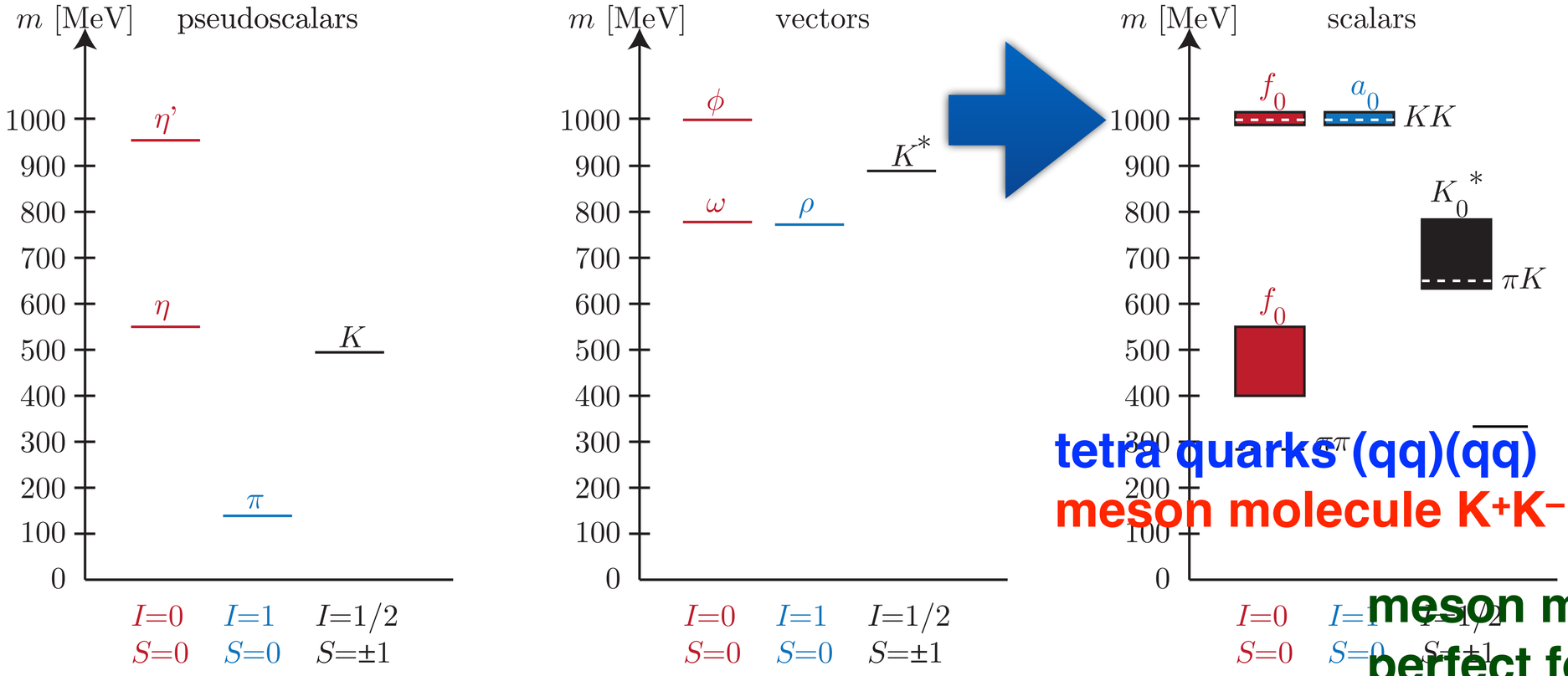

tetra quarks (qq)(qq)

meson molecule K^+K^-

meson molecule is perfect for SIDM

Gell-Mann–Okubo relation

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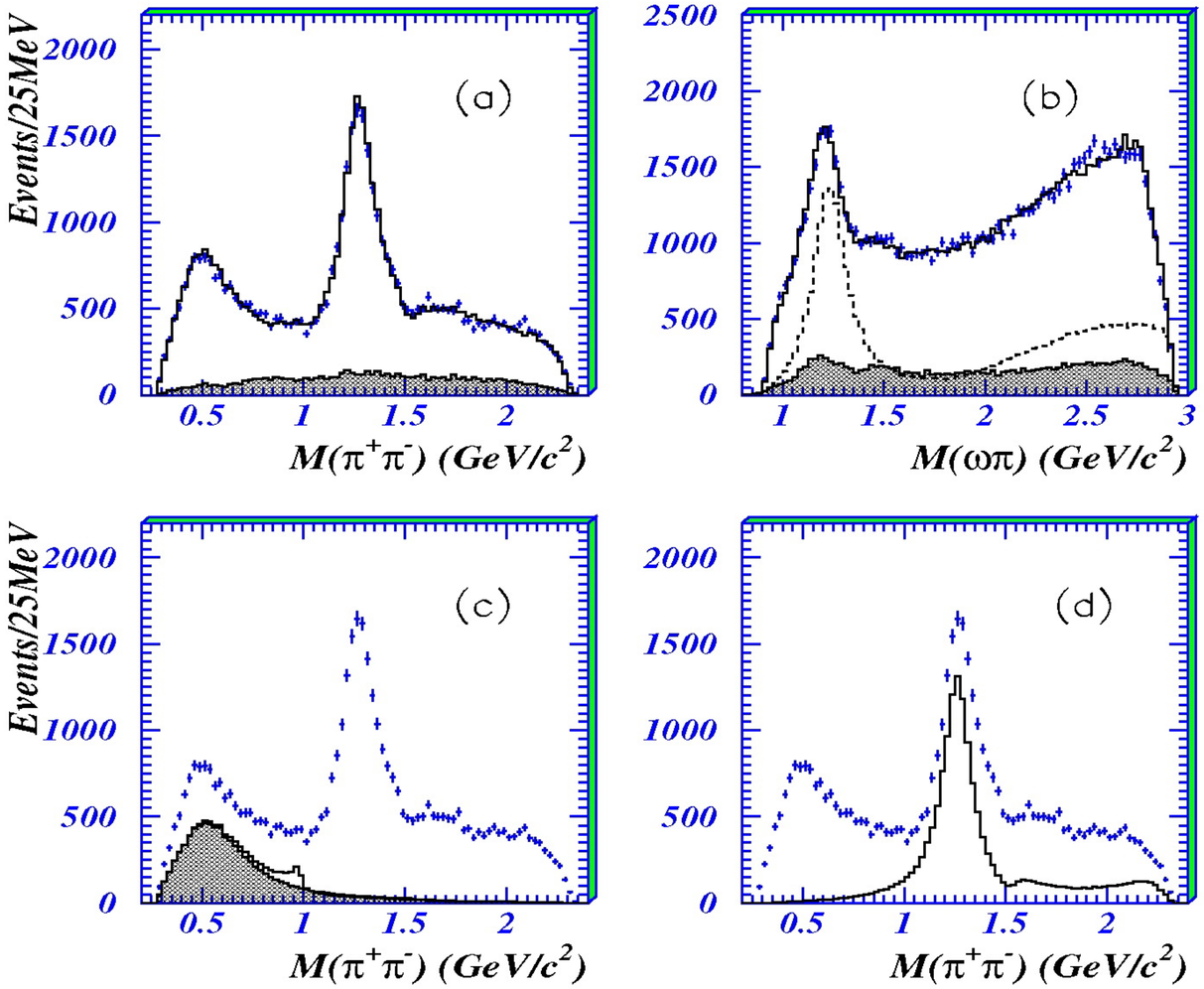
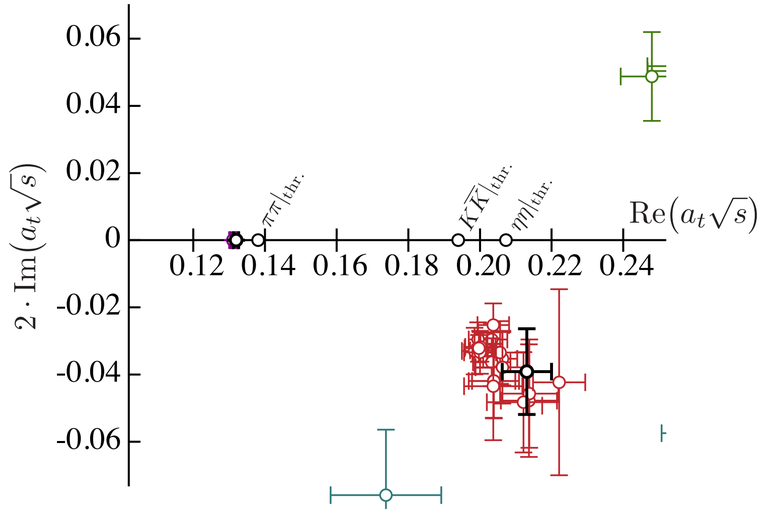
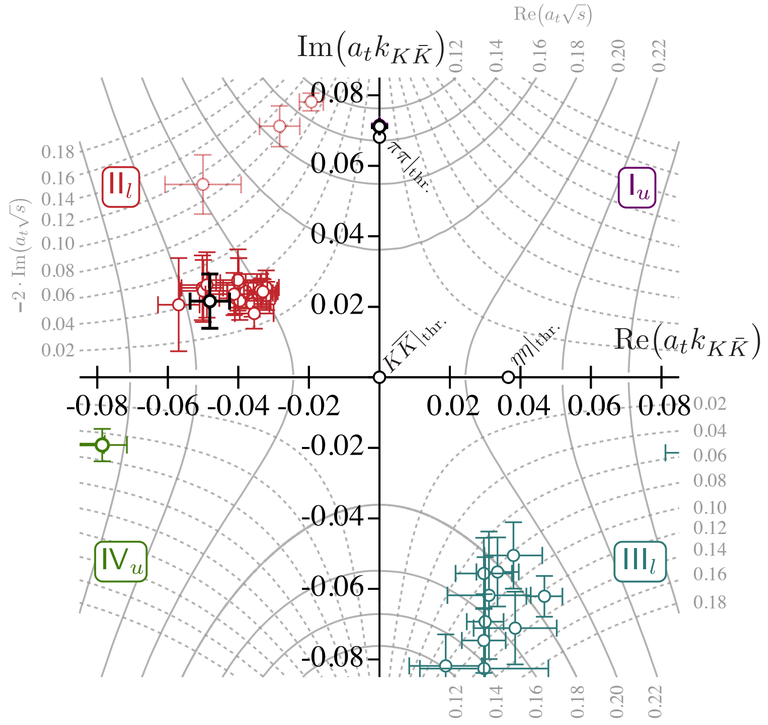


Figure 5: Figure taken from [93]. Panels (a), (b) show the $\pi^+\pi^-$ and $\omega\pi$ invariant mass projections of data from the BES analysis of $J/\Psi \to \omega\pi^+\pi^-$. Panels (c) and (d) show the $J^{PC} = 0^{++}$ and 2^{++} projections, respectively. The shaded area in (c) corresponds to the σ contribution. The contribution of the $f_0(980)$ can be seen as a small peak on top of the shaded area right below 1 GeV. Compare the height of the peak and the asymmetric shape of the σ in (c) to the height and shape of the $f_2(1275)$ resonance in (d). Reprinted from Phys. Lett. B **598**, 149, 2004, M. Ablikim *et al.* [BES Collaboration], "The sigma pole in $J/\psi \to \omega\pi^+\pi^-$,". Copyright 2004, with permission from Elsevier.

Caption Box

We learn from lattice





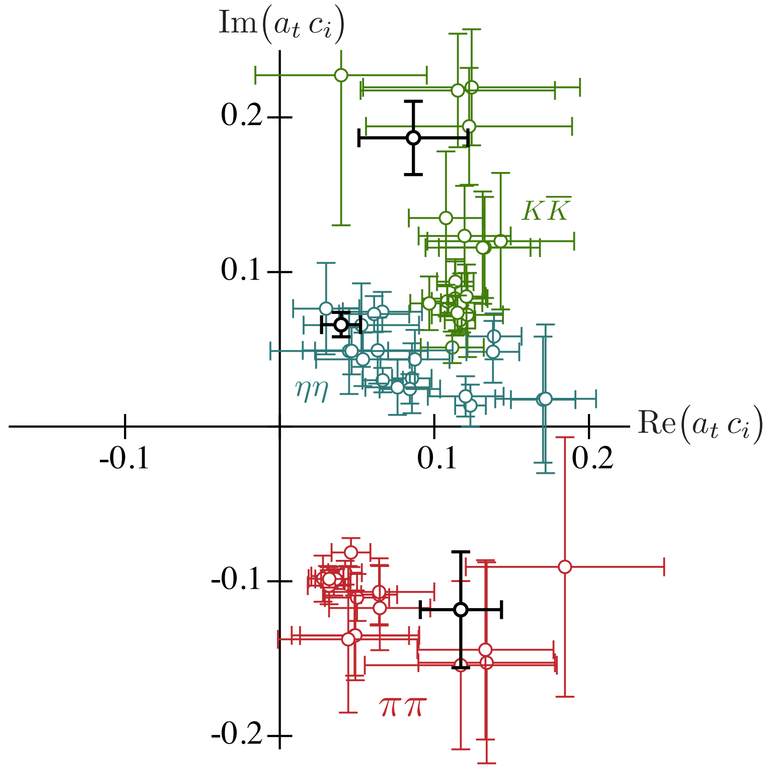
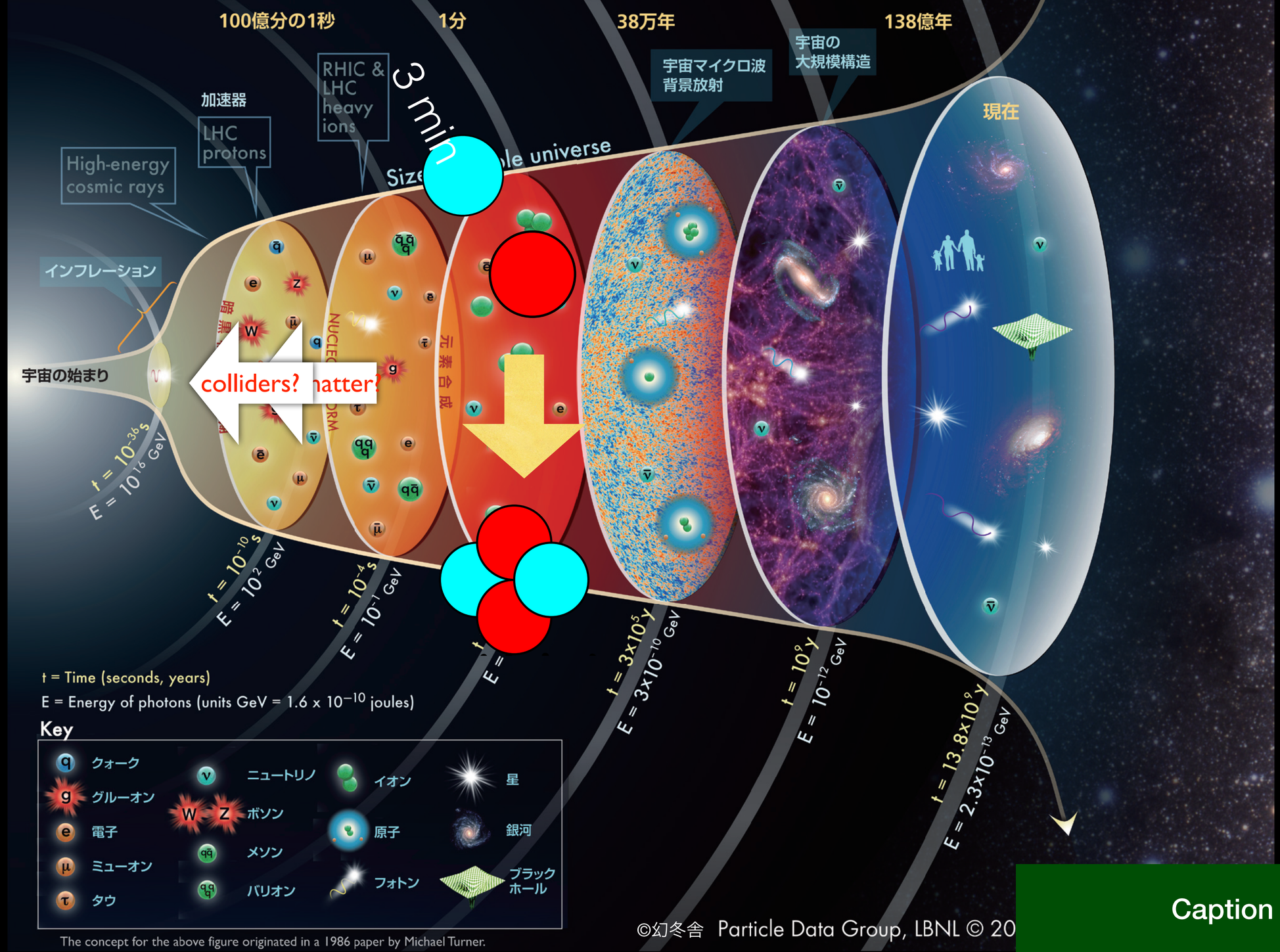


FIG. 16. Couplings for the 20 S-wave amplitudes discussed in Section III B from factorized residues at the sheet II pole. Thick black points indicate the particular amplitude defined by Eq. 3.

'background'. Given this, it is worth
to describe just that part of the spec
$a_t E_{\mathrm{cm}} = 0.17$ using amplitudes that
an explicit σ bound-state pole. In Fig

Caption Box



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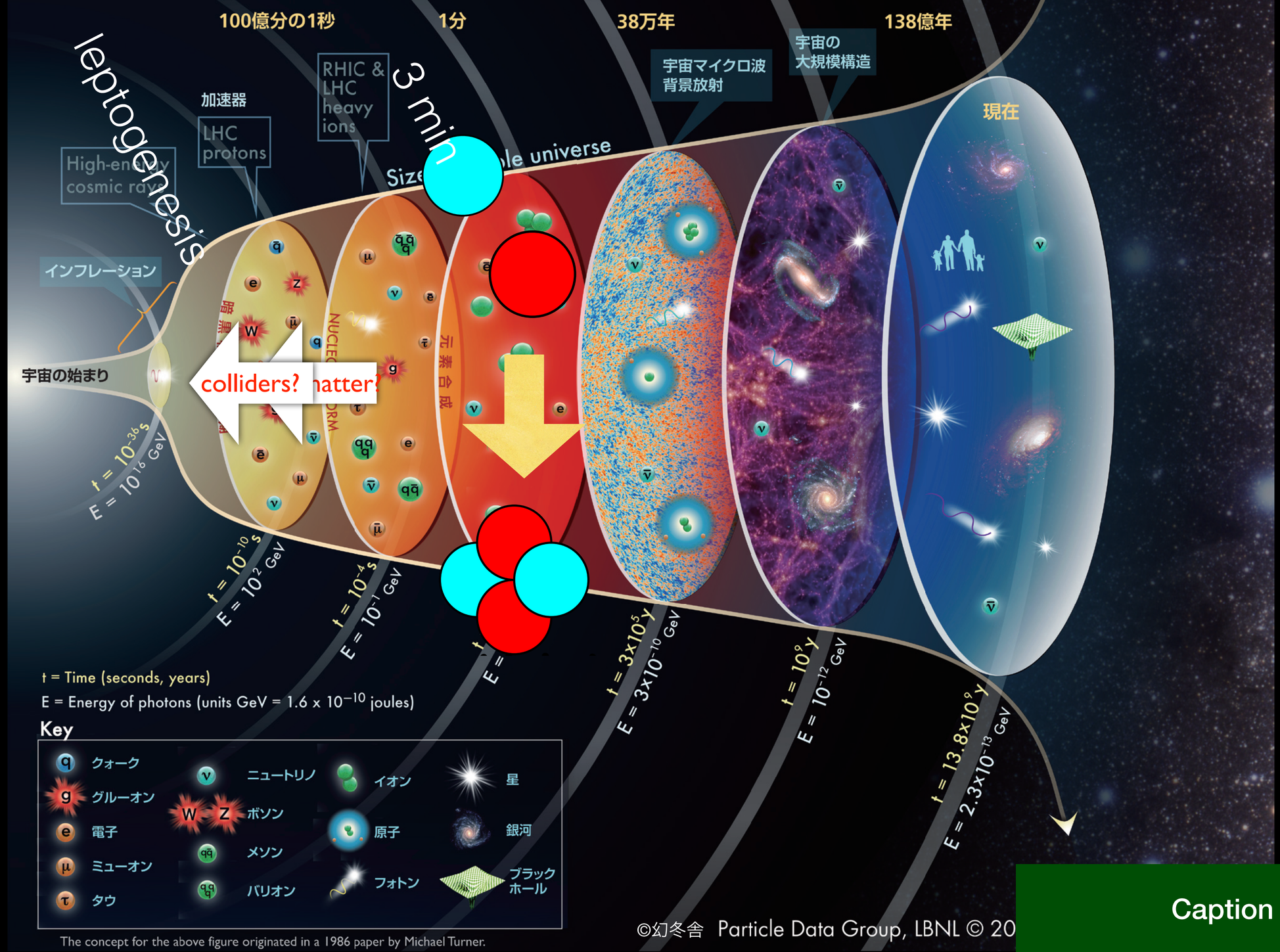
100億分の1秒
1分
38万年
138億年
leptogenesis
3 min
RHIC & LHC heavy ions
加速器
LHC protons
High-energy cosmic rays
宇宙マイクロ波背景放射
宇宙の大規模構造
現在
インフレーション
宇宙の始まり
colliders?
matter?
元素合成
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 3 \times 10^{5}$ y
$E = 3 \times 10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ GeV
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E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)
Key
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ミューオン
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ニュートリノ
ボソン
メソン
バリオン
イオン
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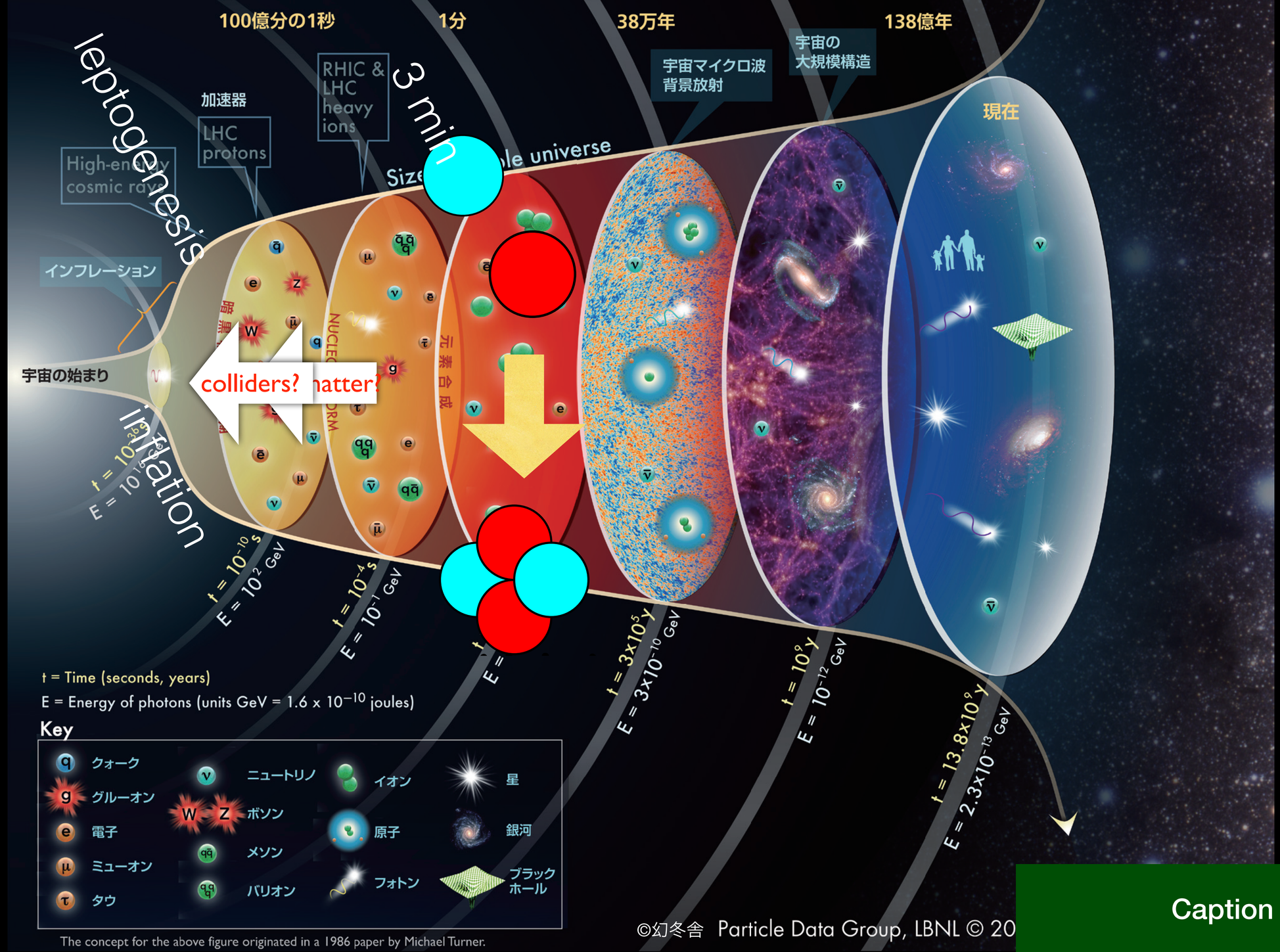
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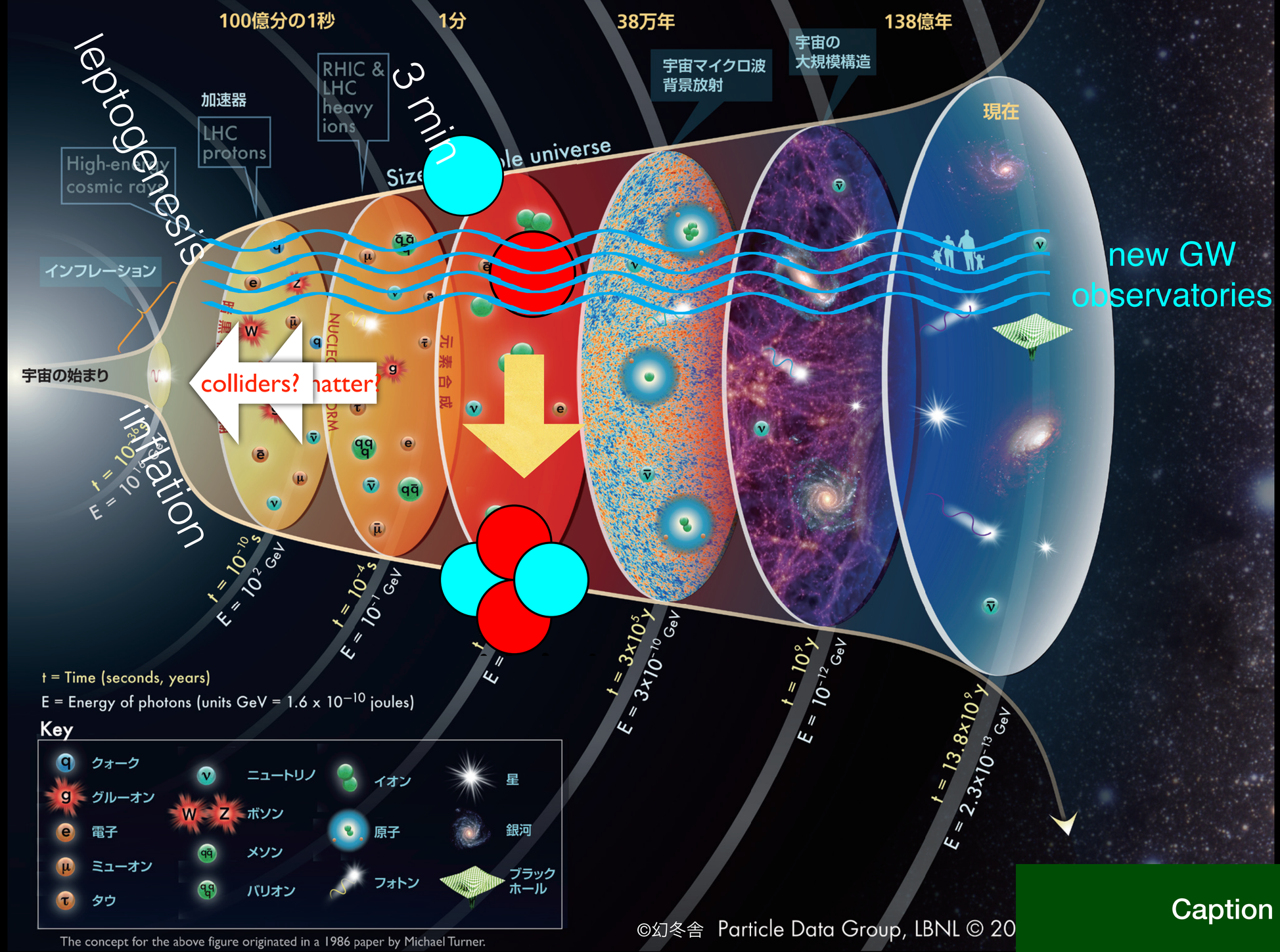

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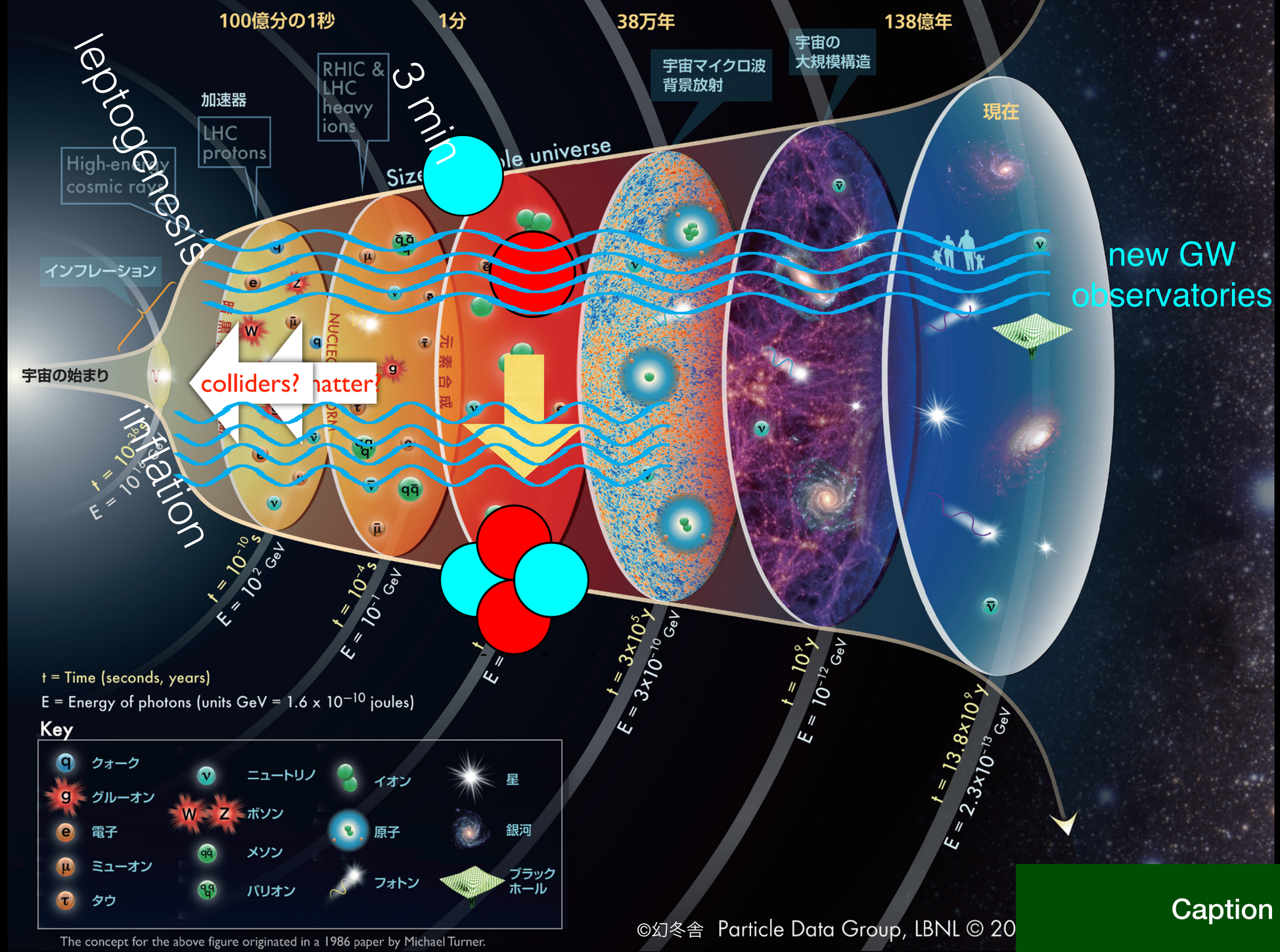
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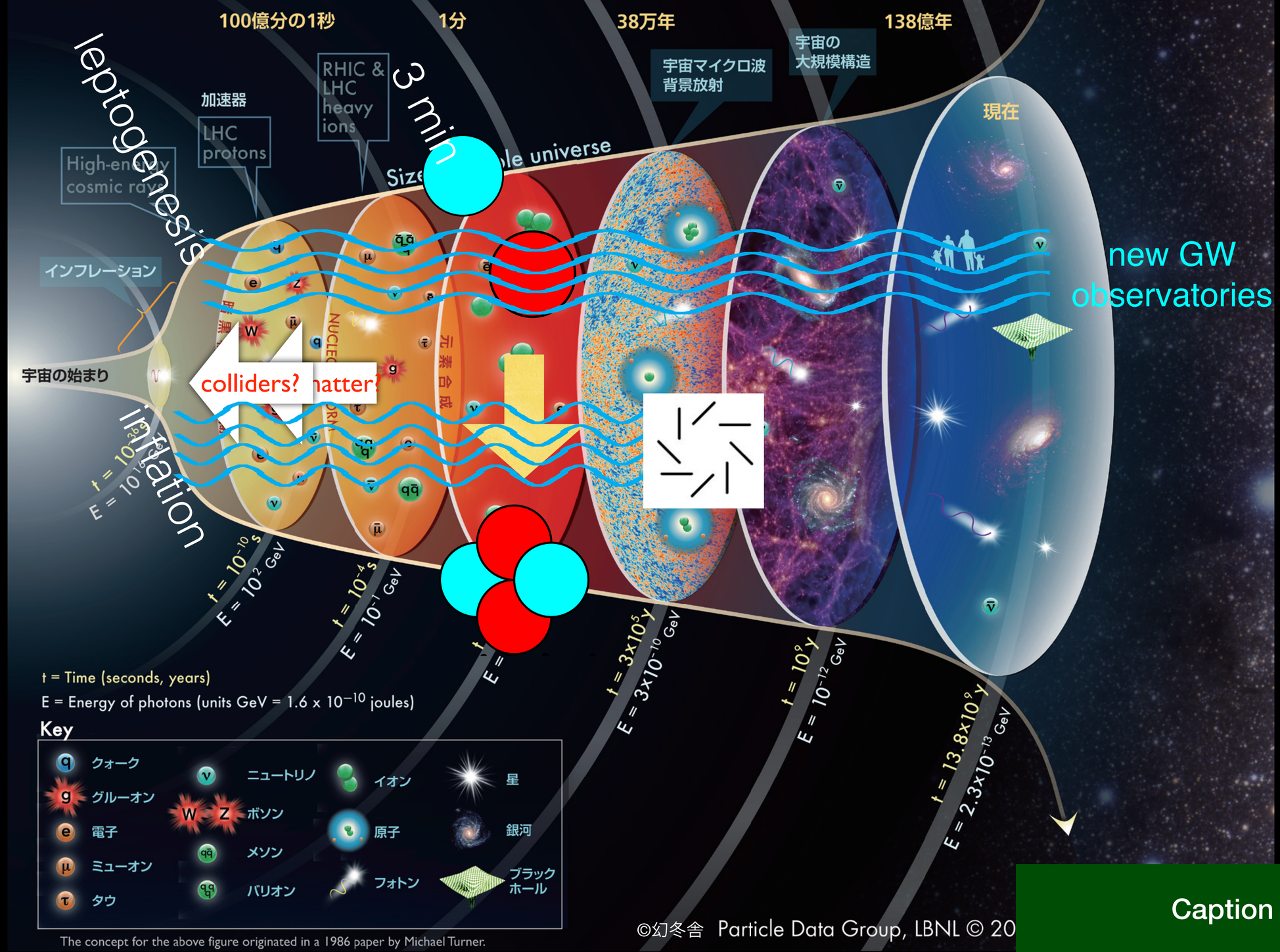

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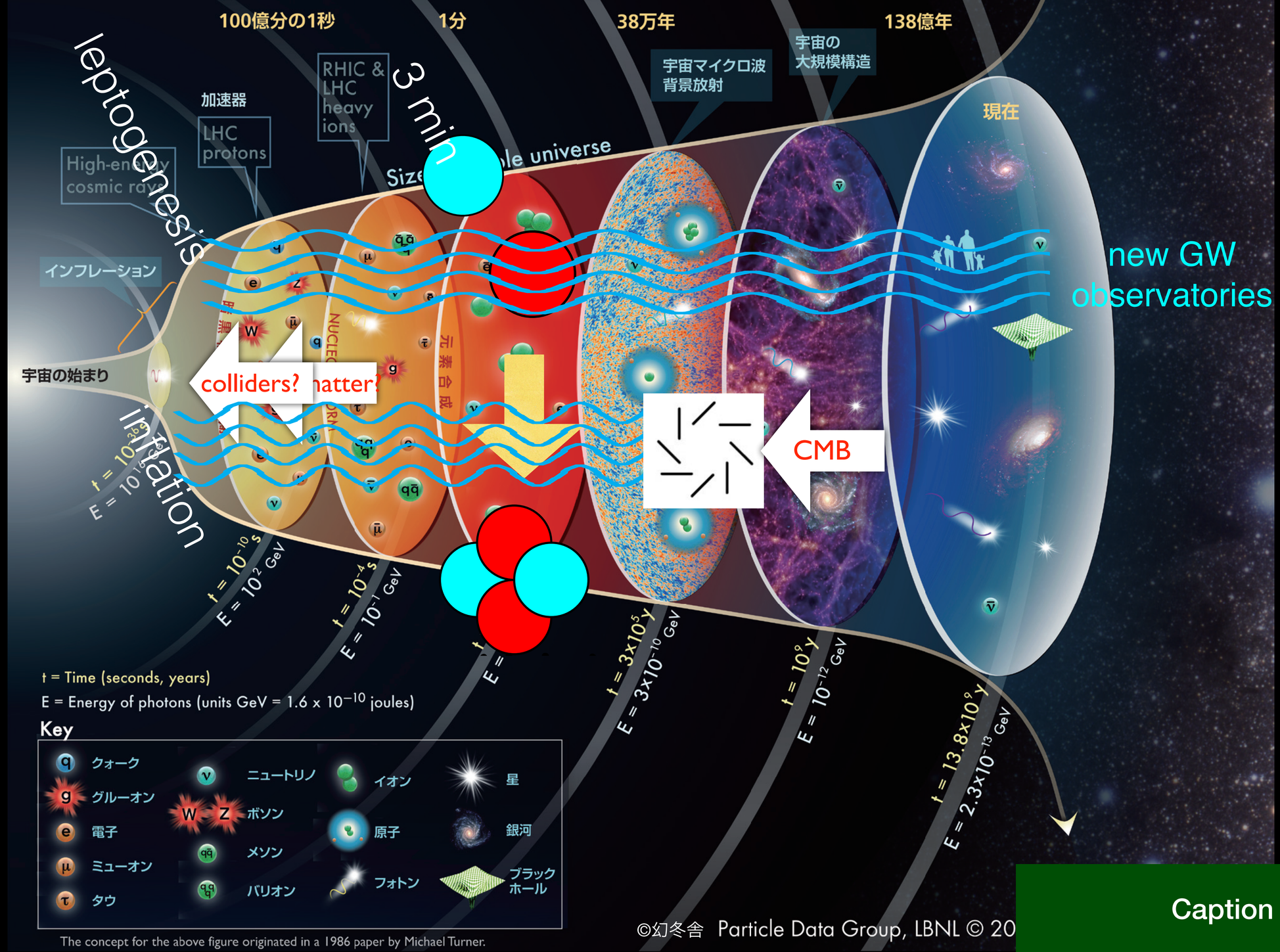
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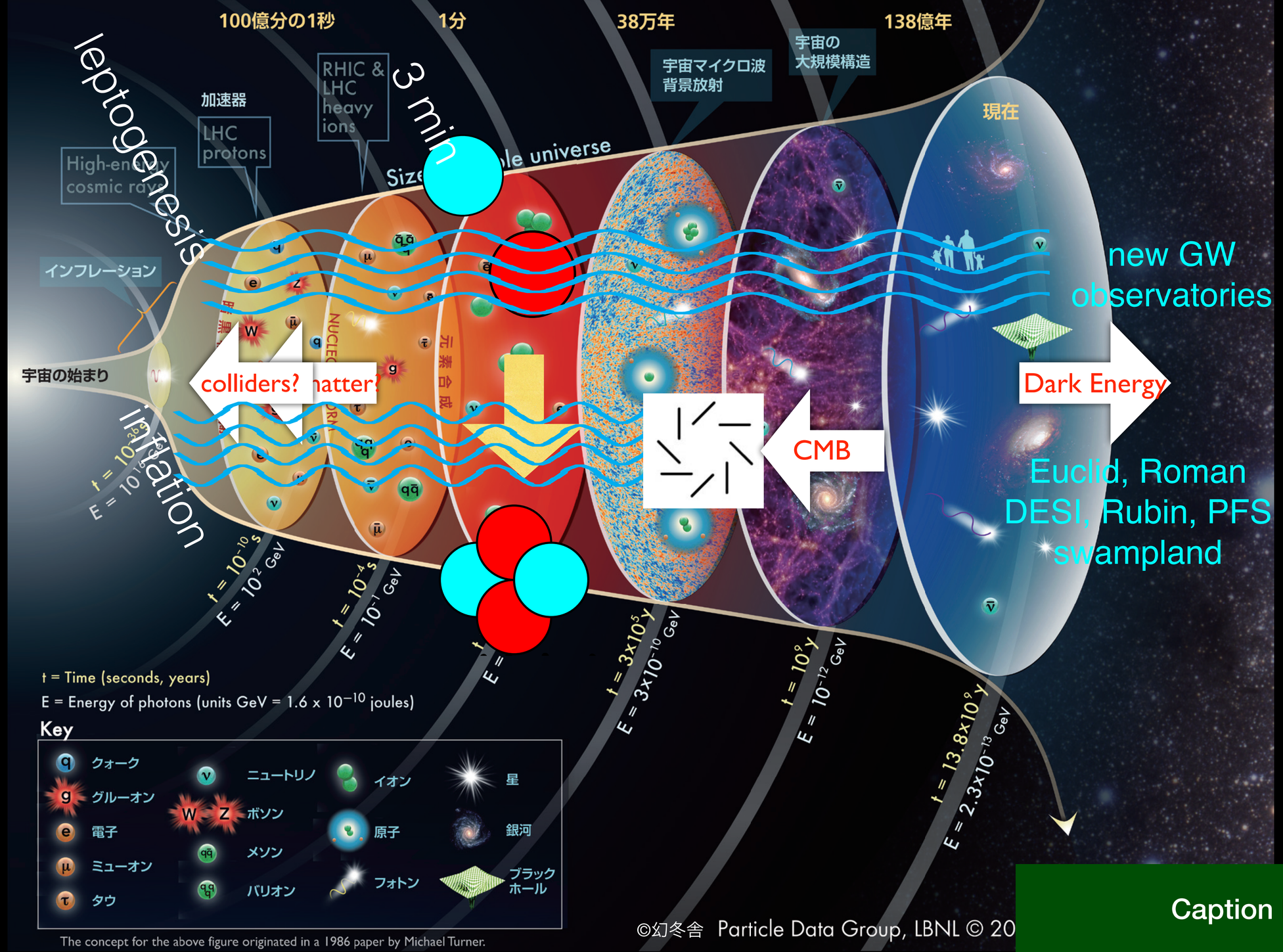
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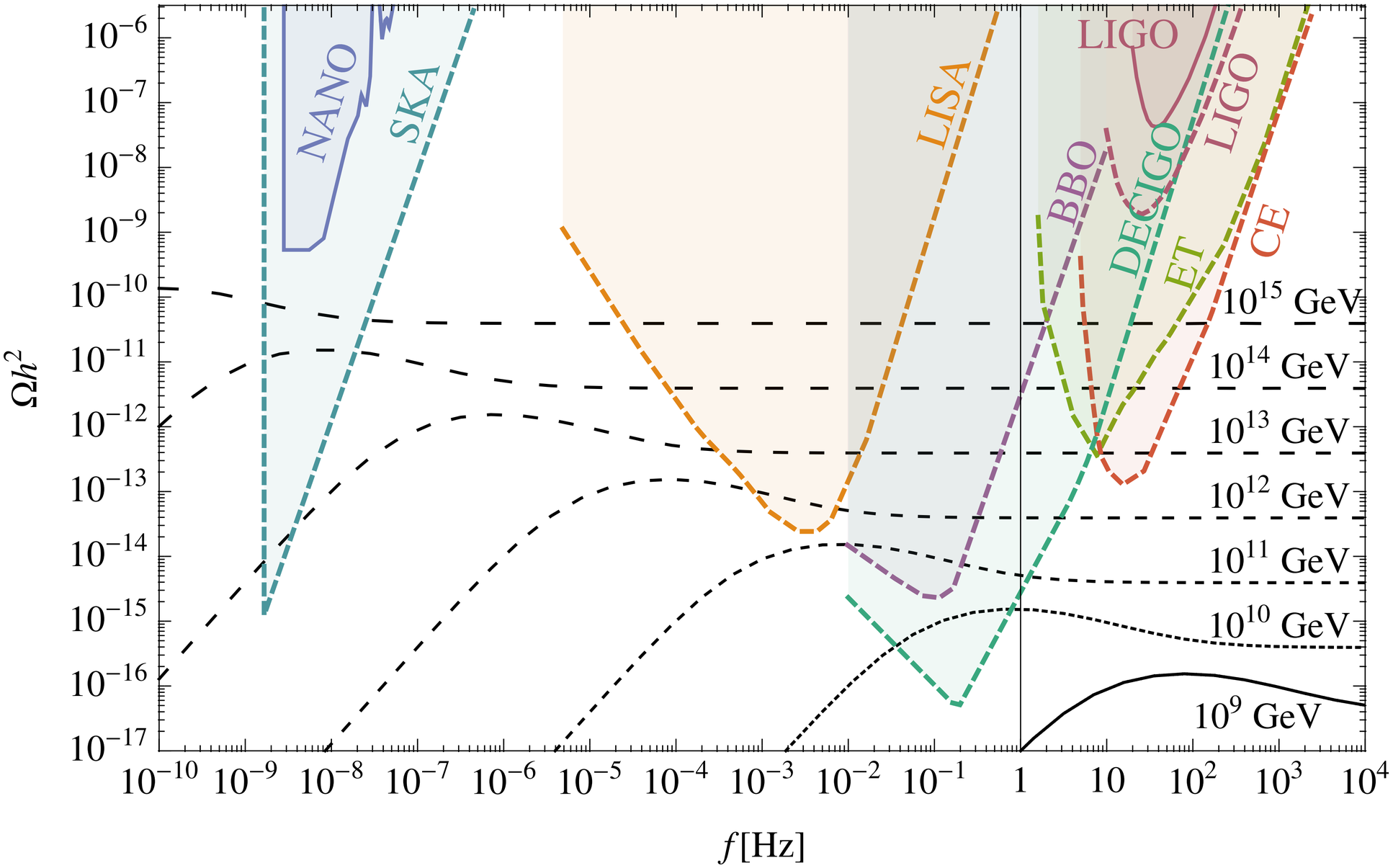
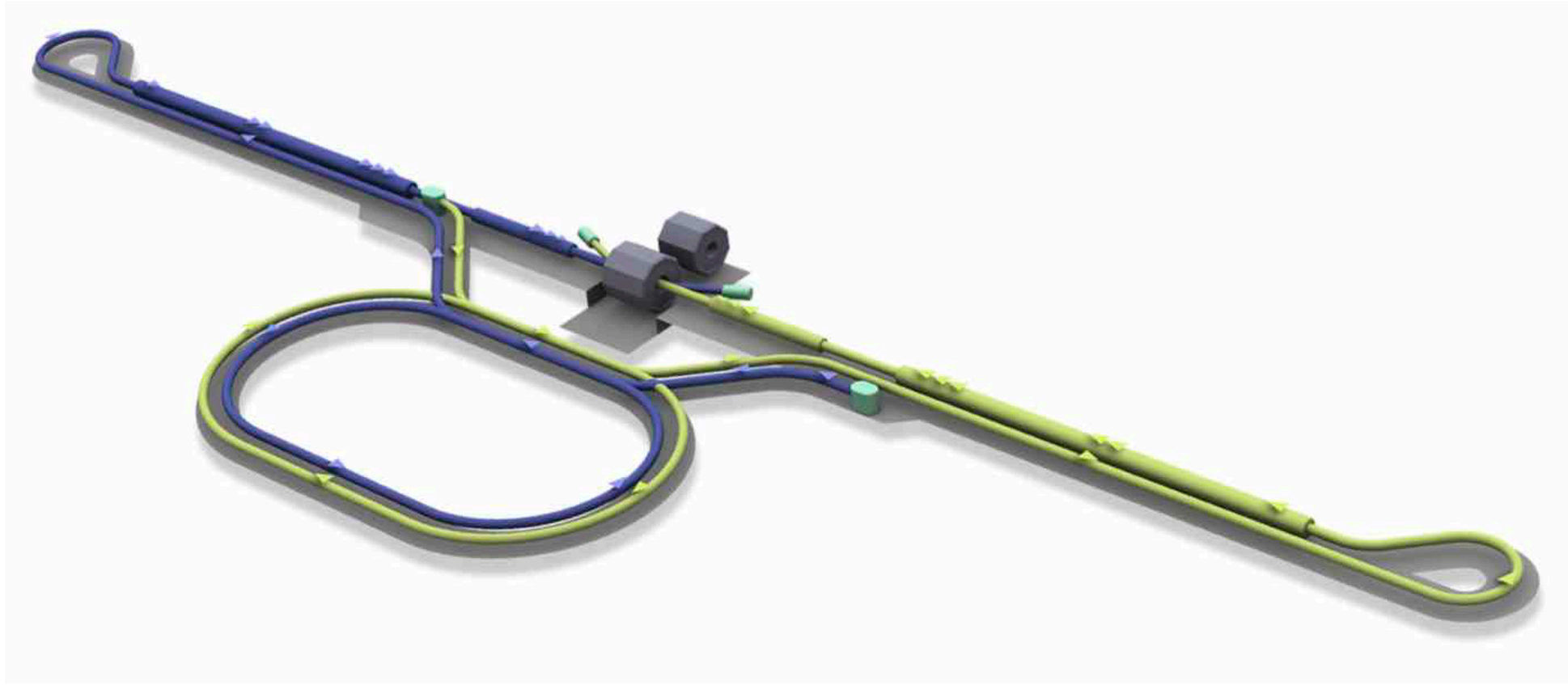


J. Dror, T. Hiramatsu, K. Kohri, HM, G. White, arXiv:1908.03227

covers pretty much the entire range for leptogenesis!

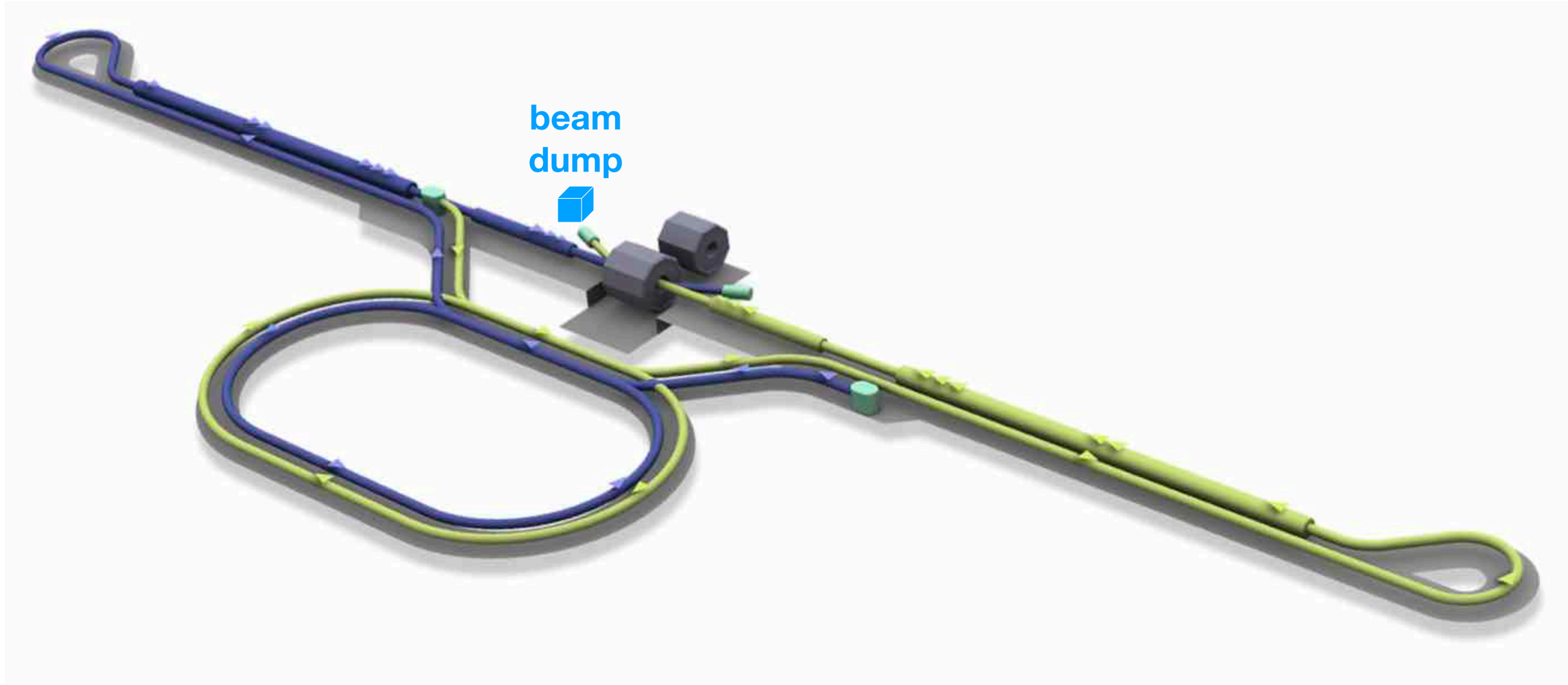
Caption Box

new ideas for new facilities



Caption Box

new ideas for new facilities



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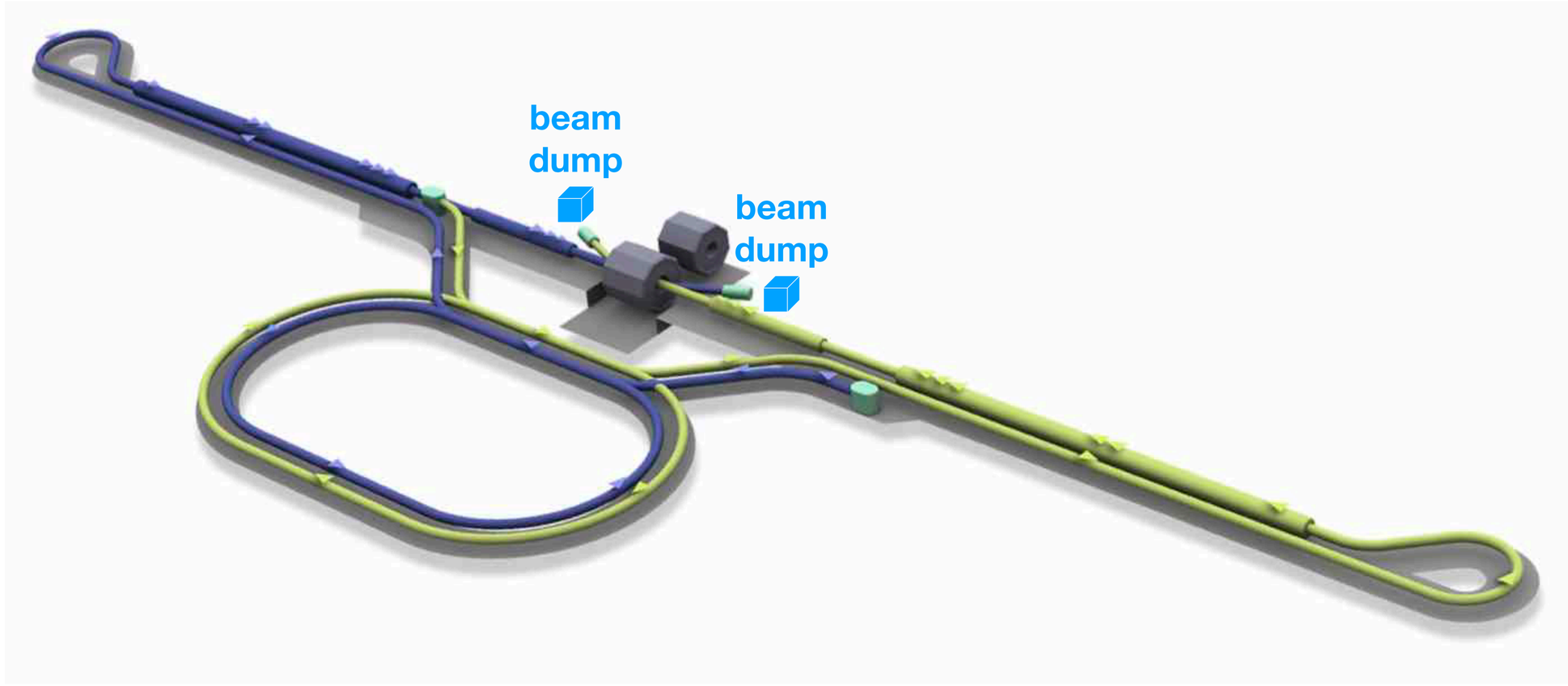
new ideas for new facilities



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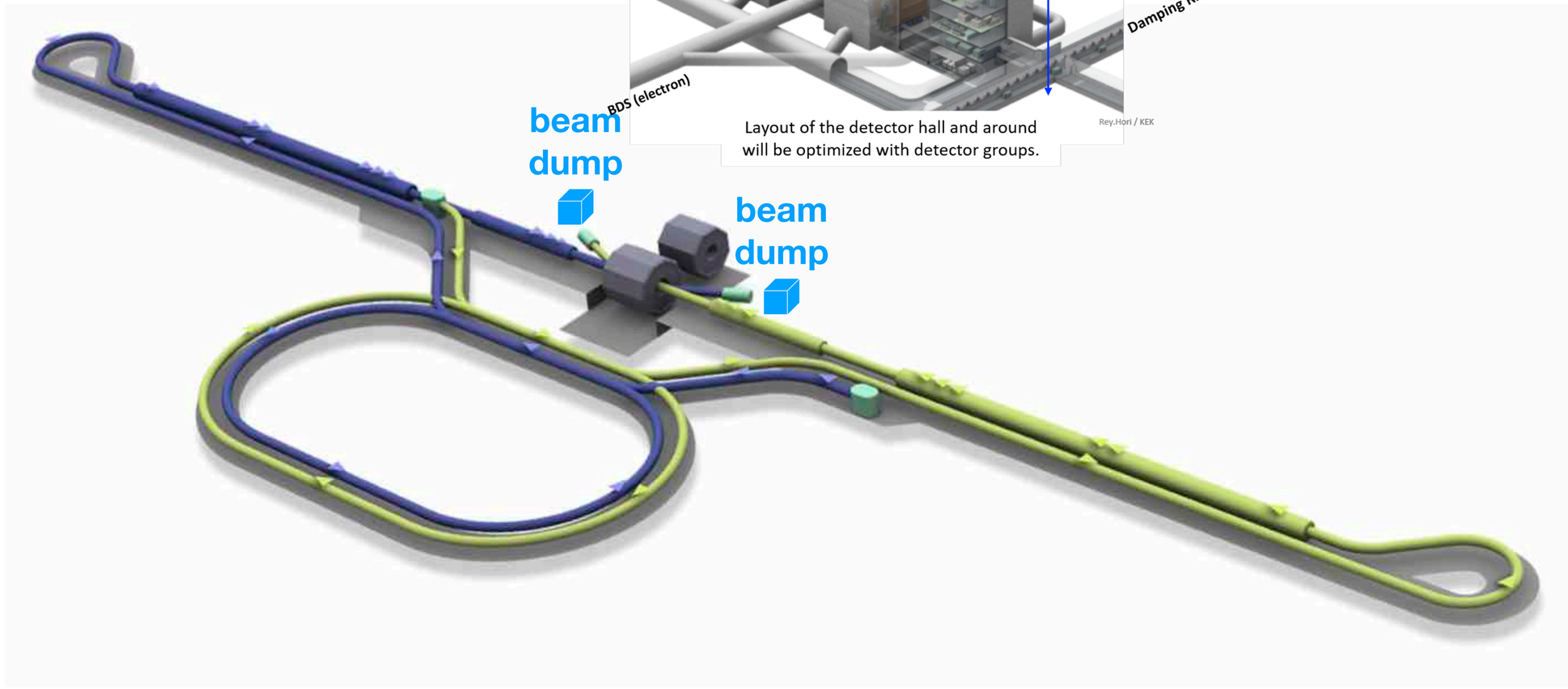
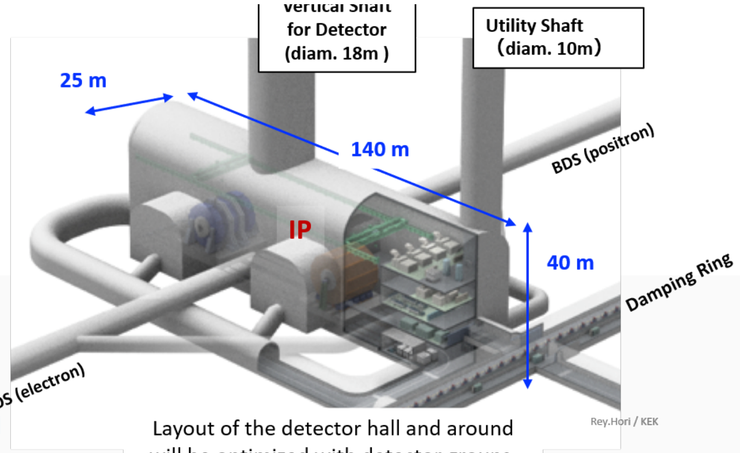
new ideas for new facilities

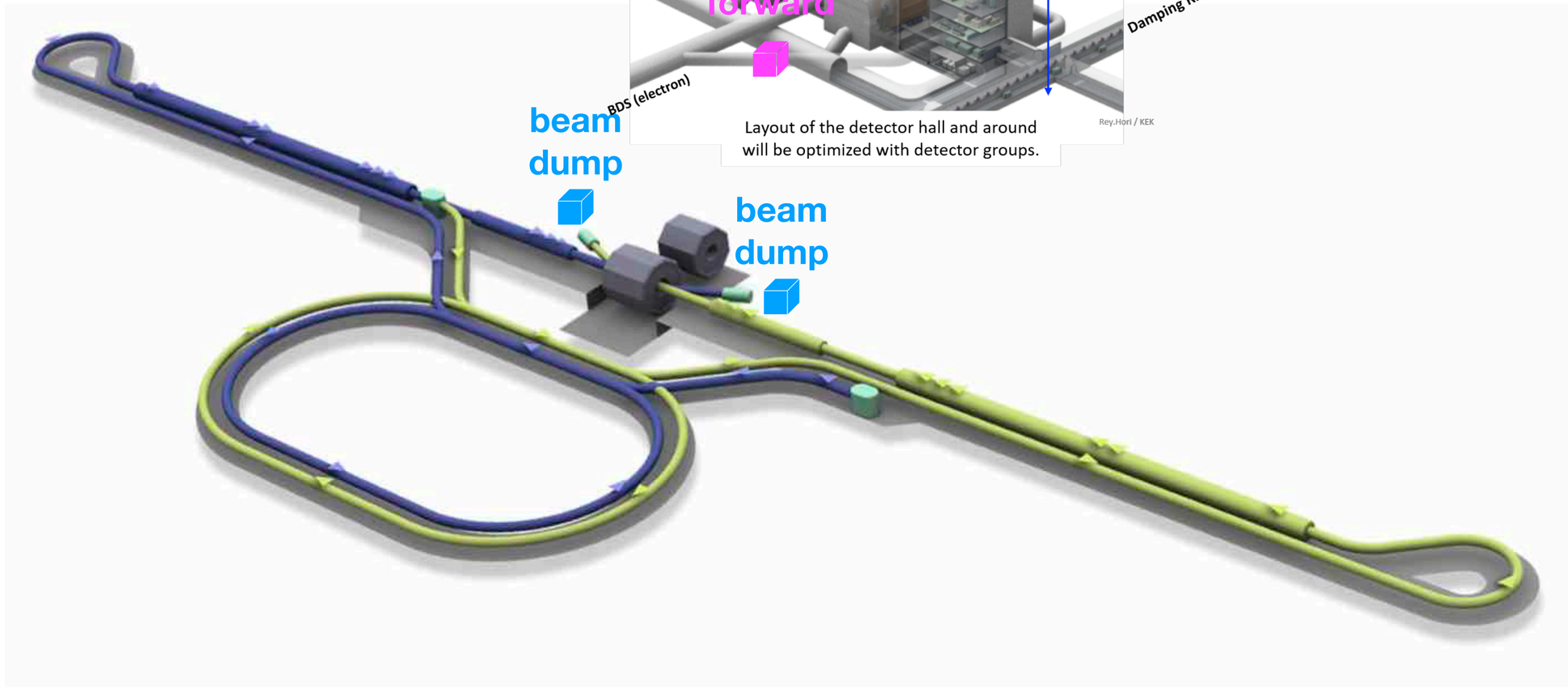




Layout of the detector hall and around will be optimized with detector groups.

Caption Box

new ideas for new facilities



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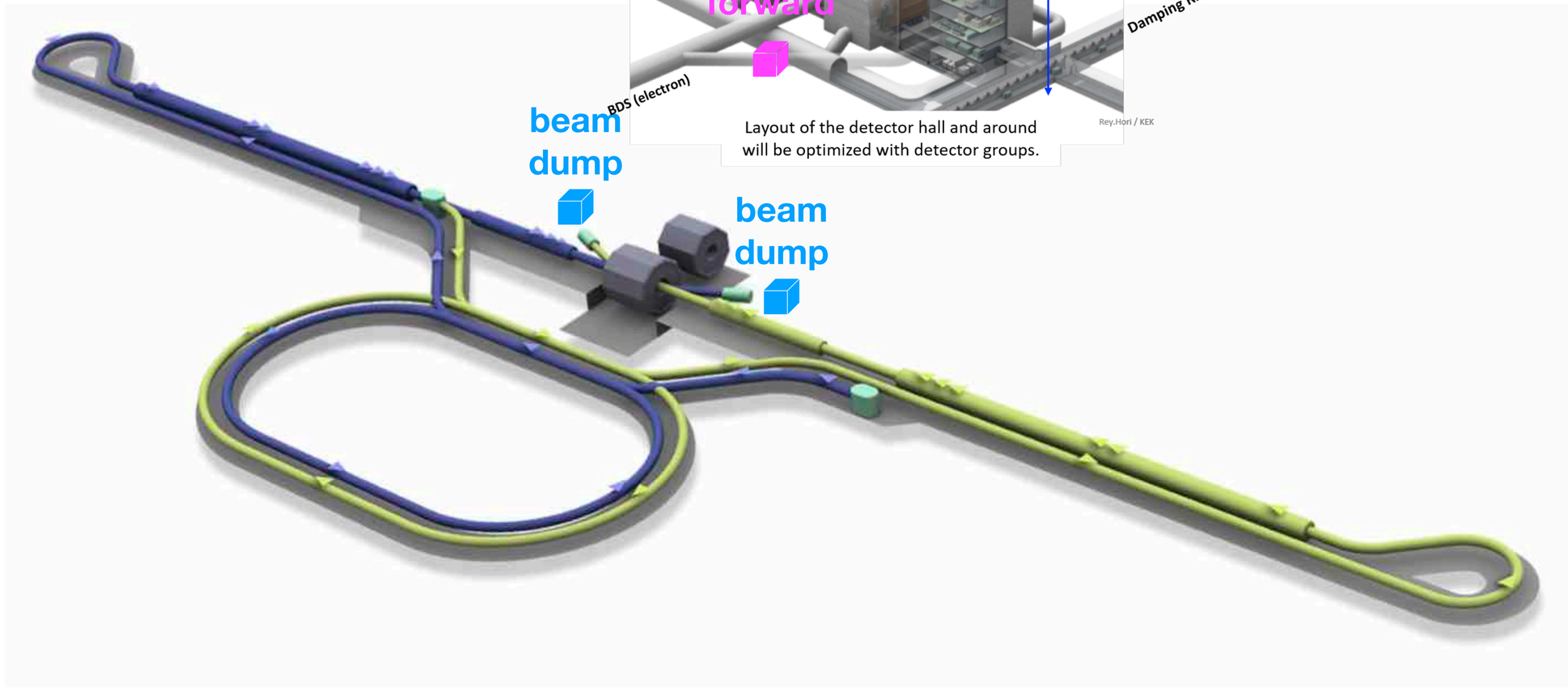

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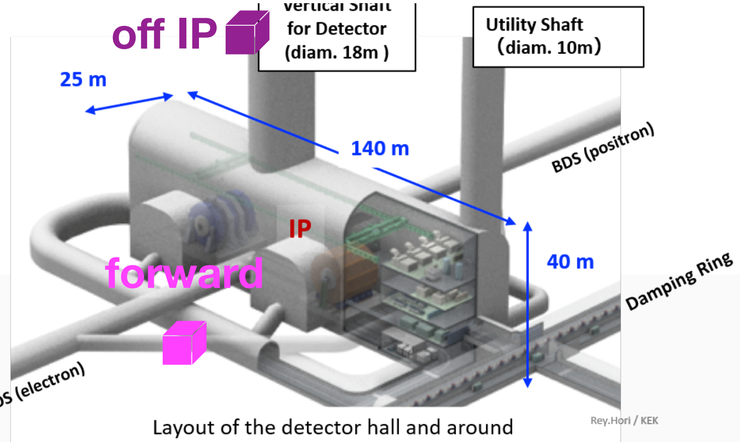

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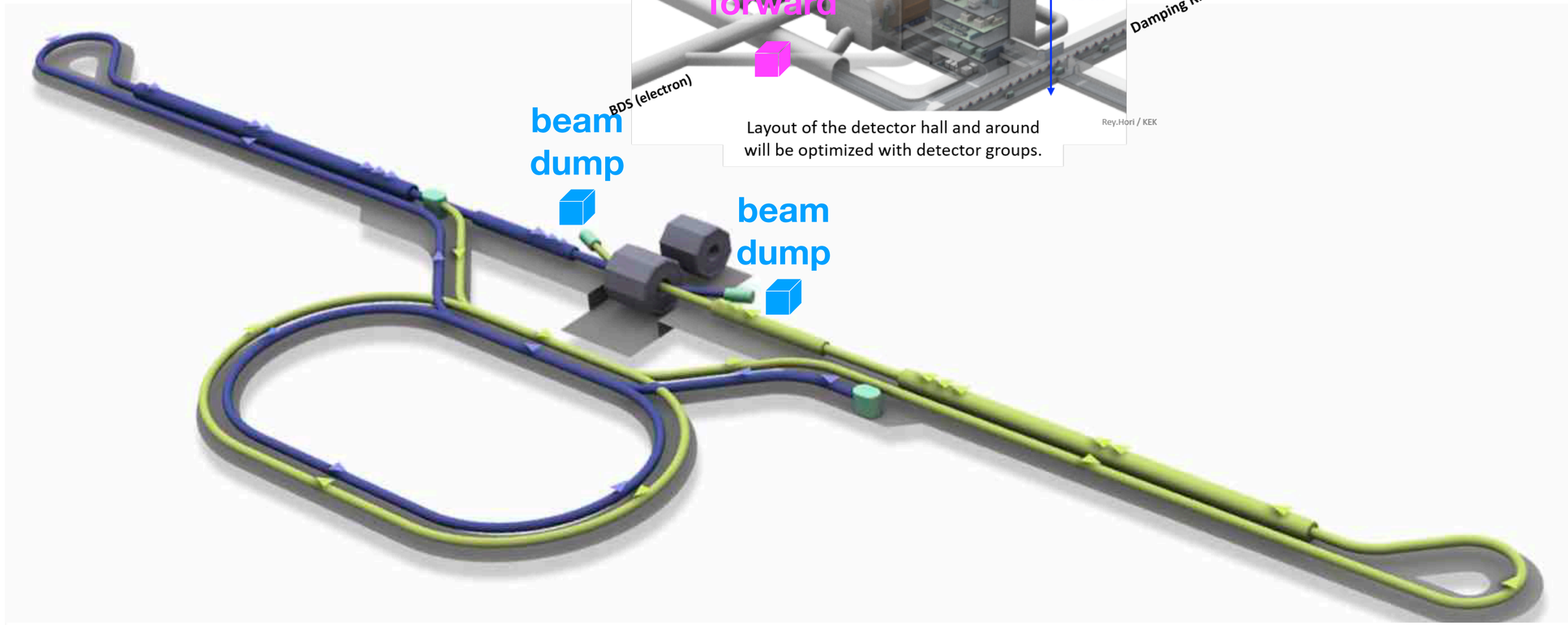

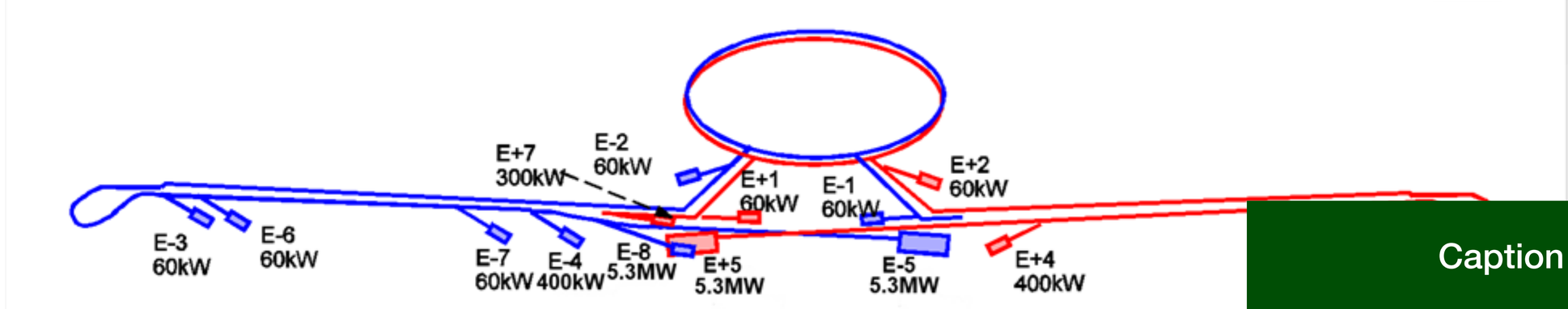

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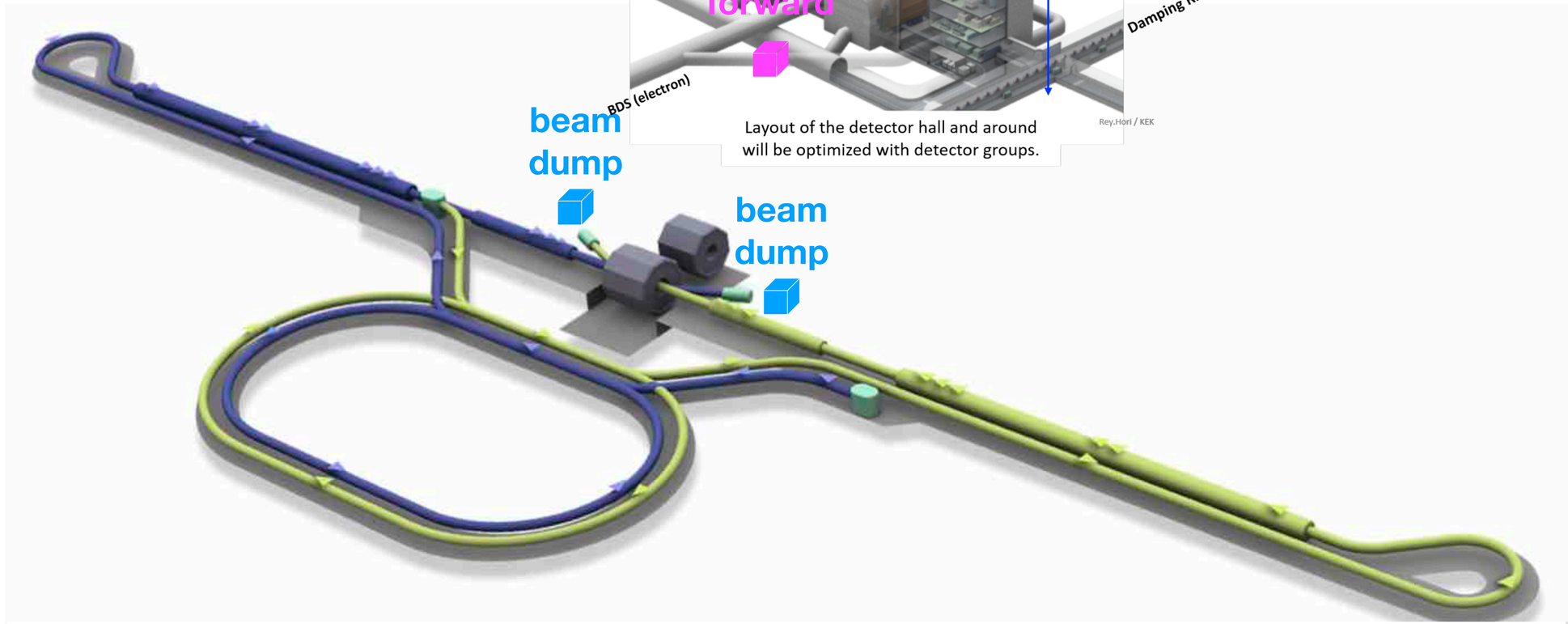

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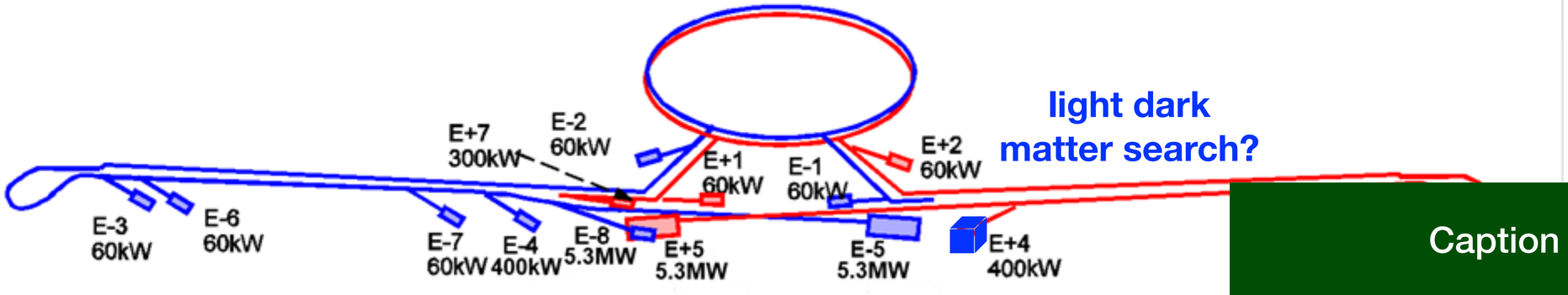

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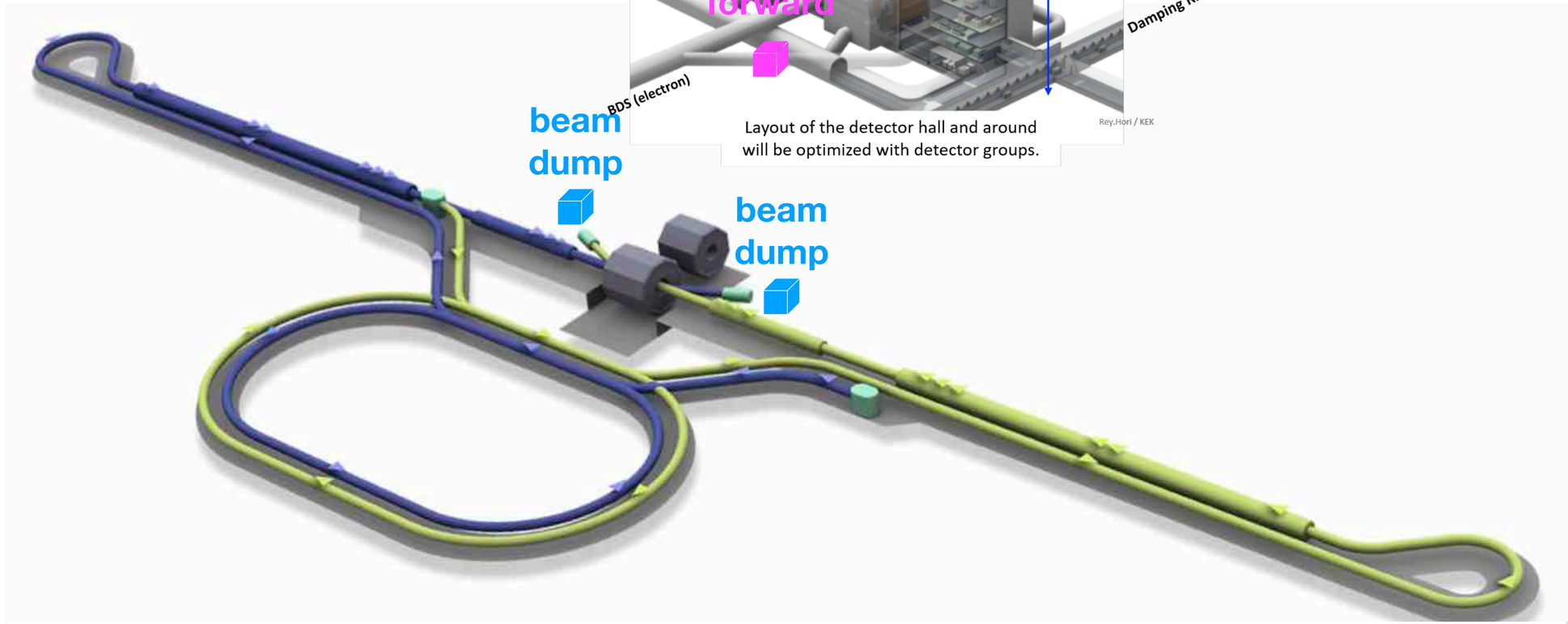

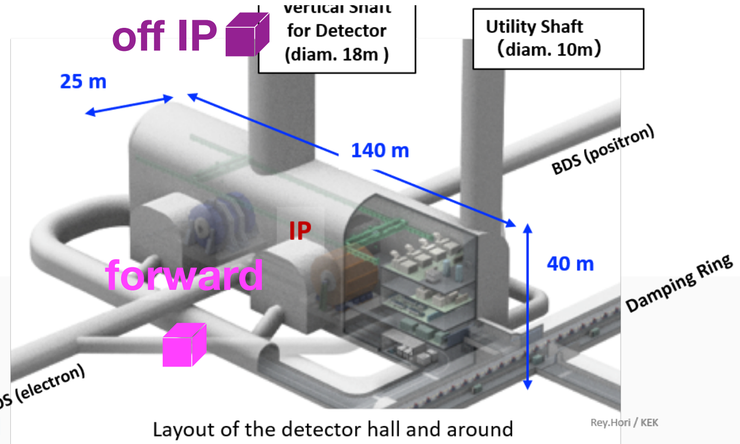

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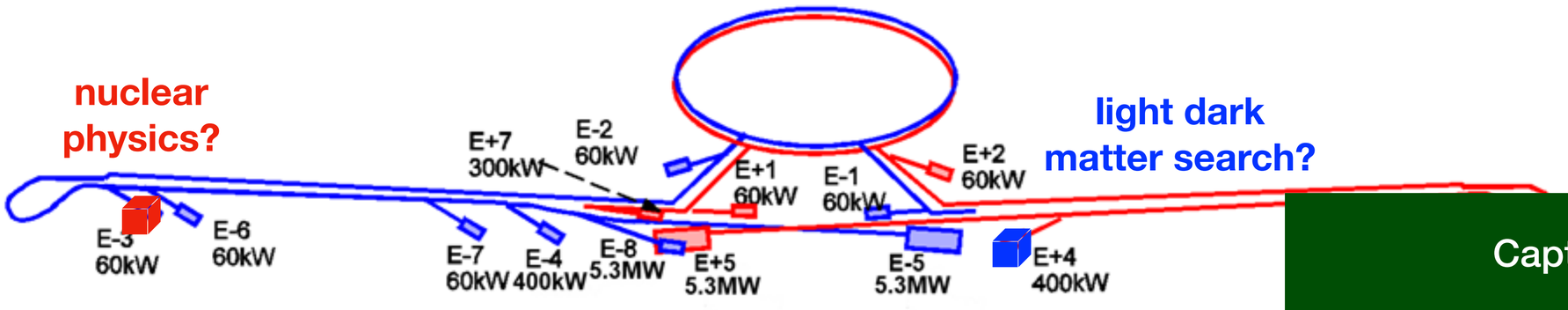

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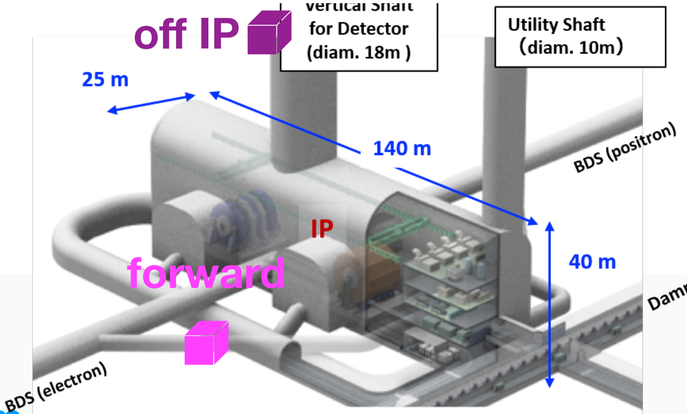

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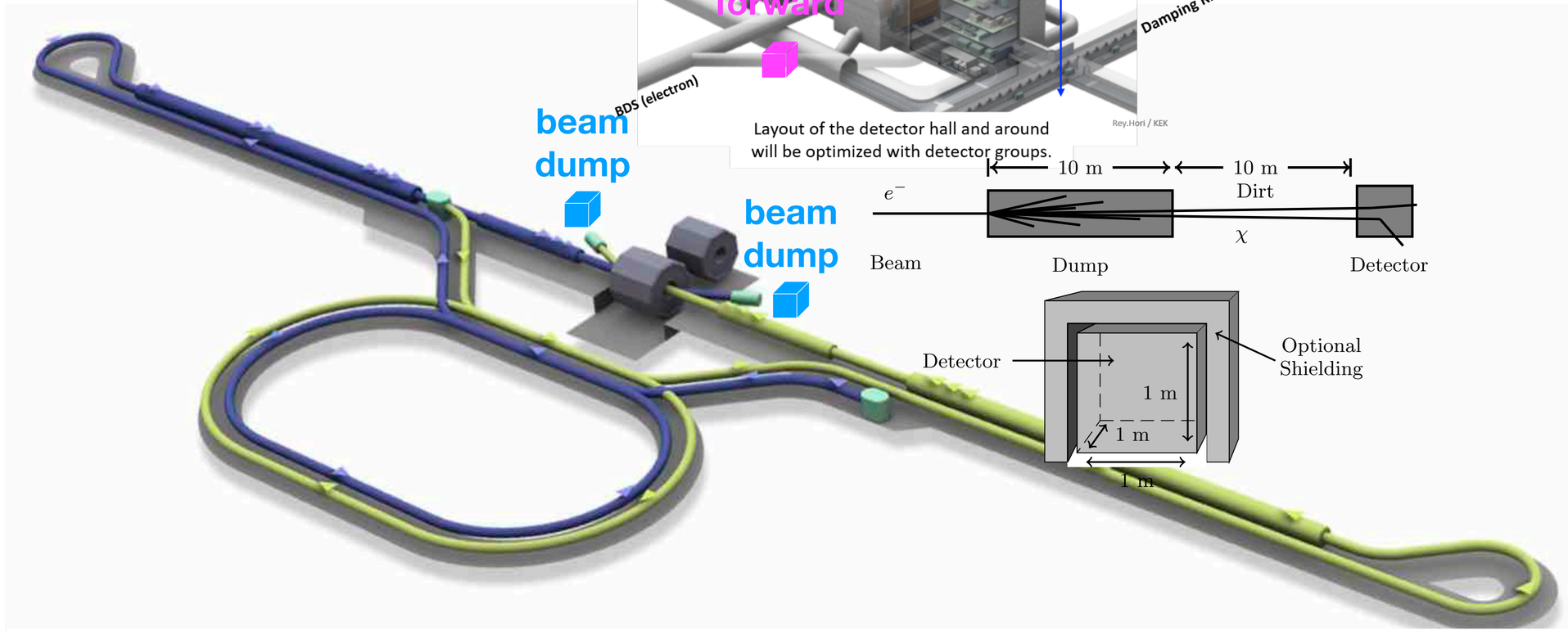

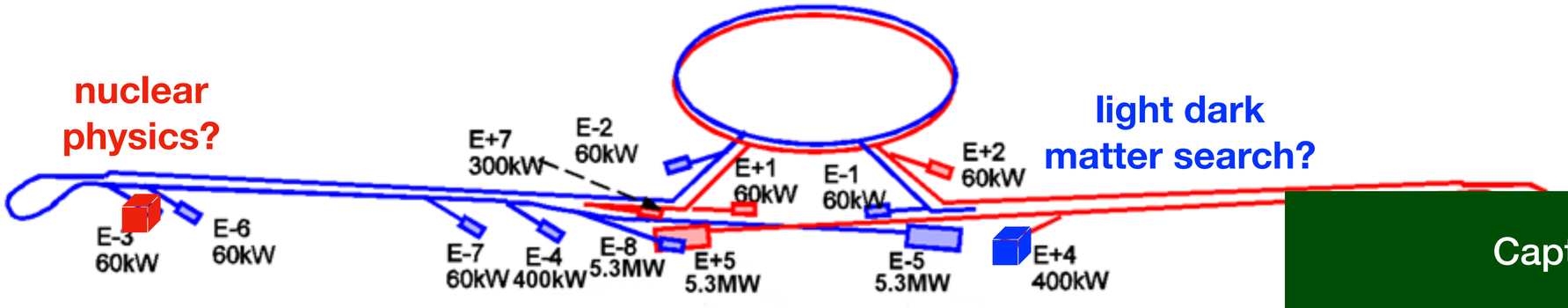

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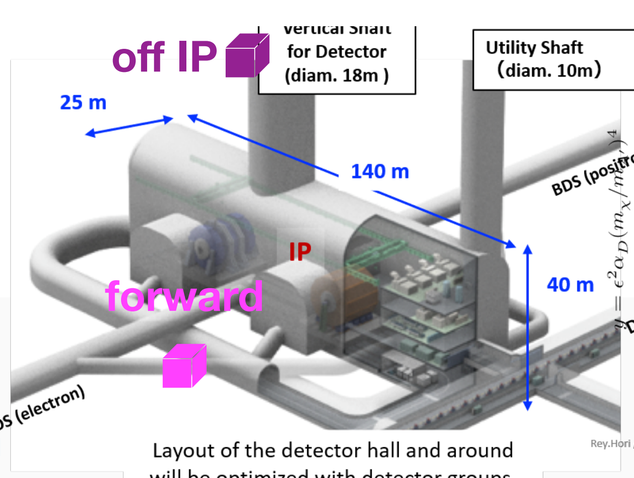

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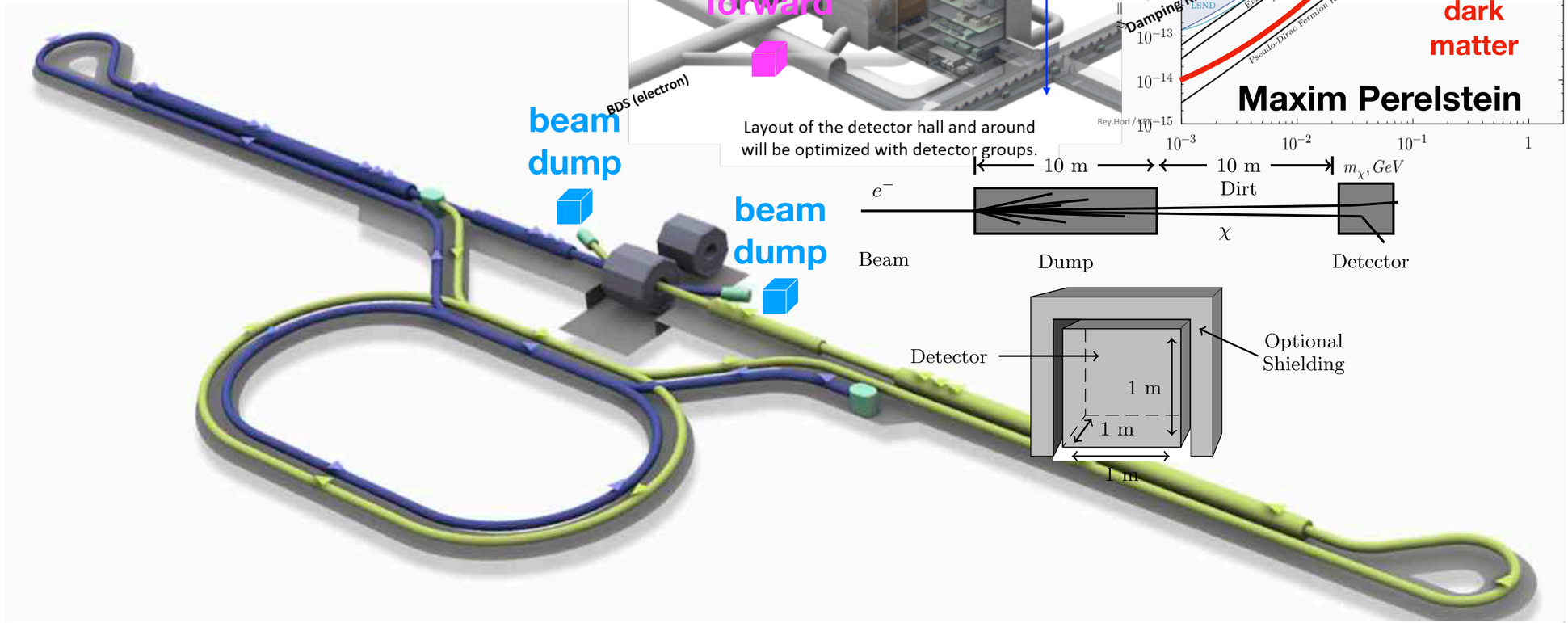

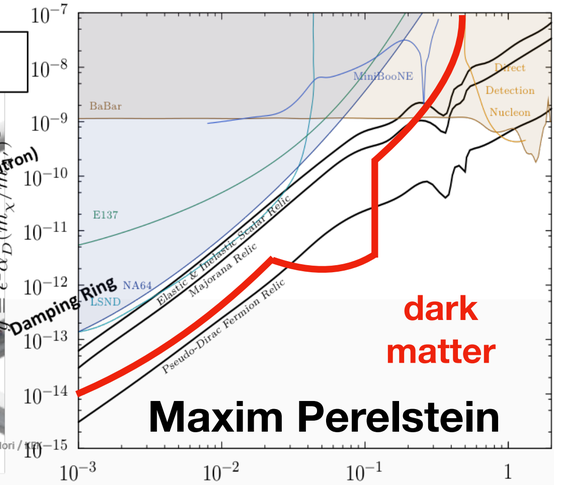

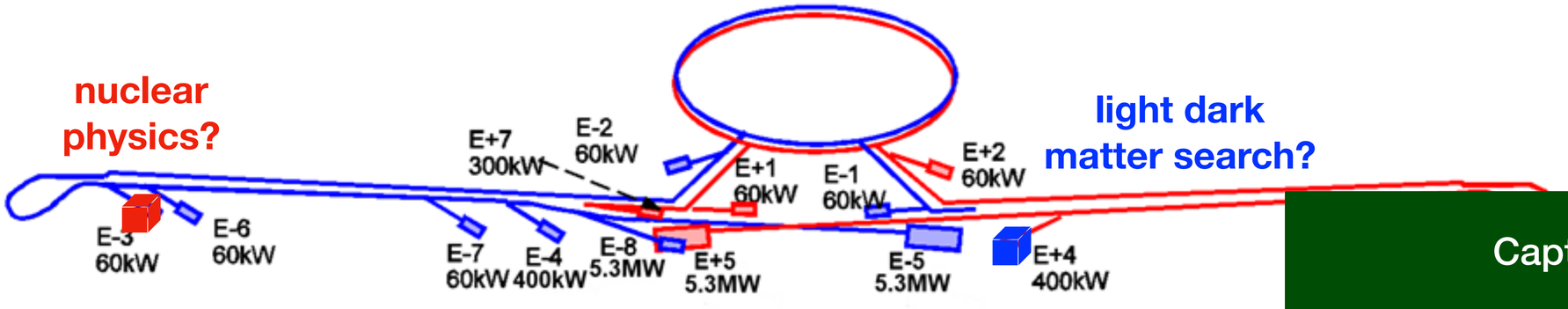

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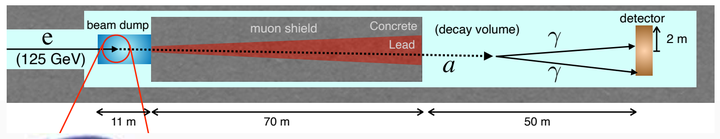

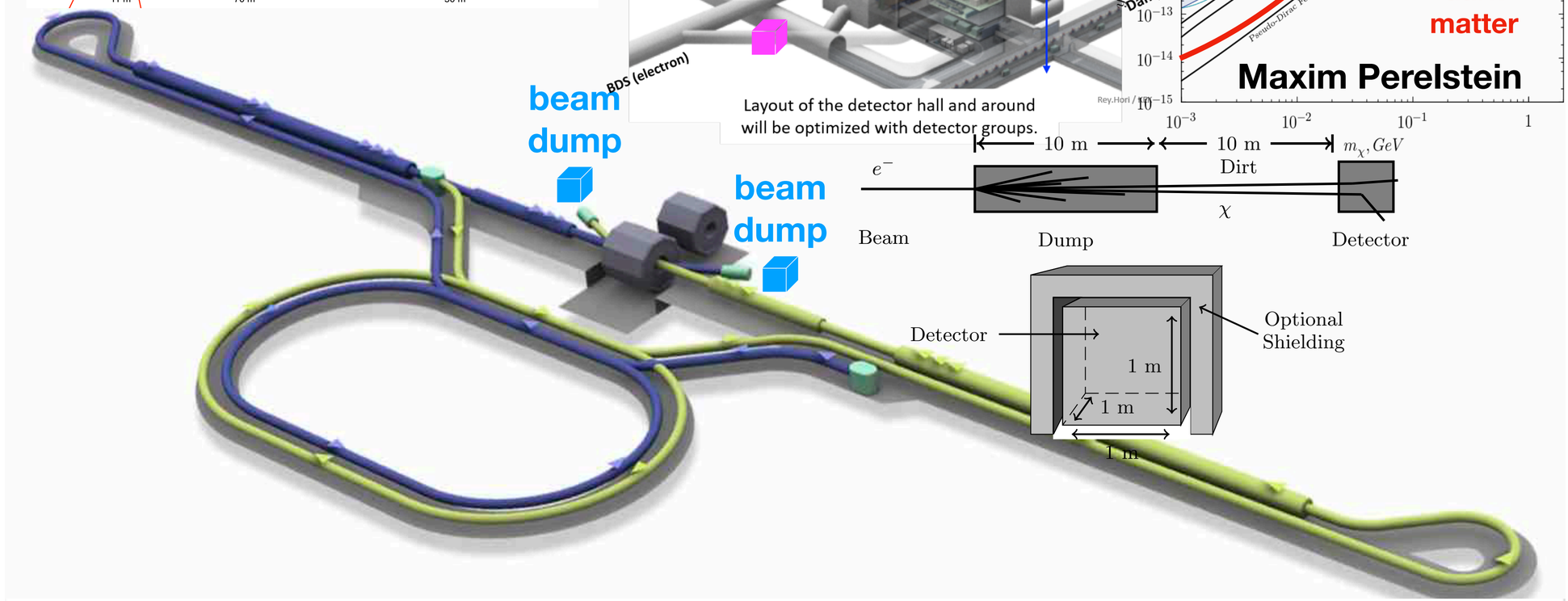

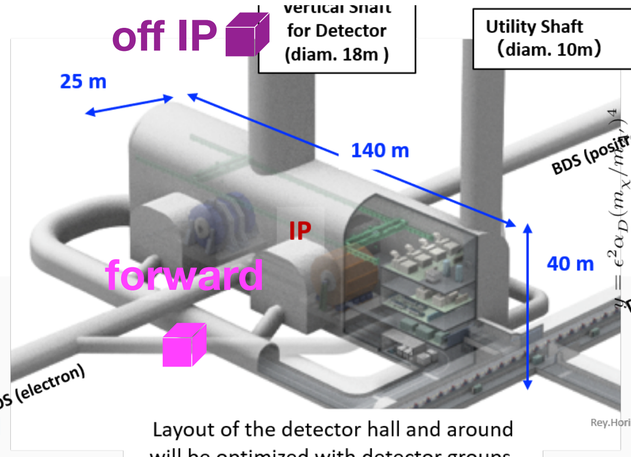

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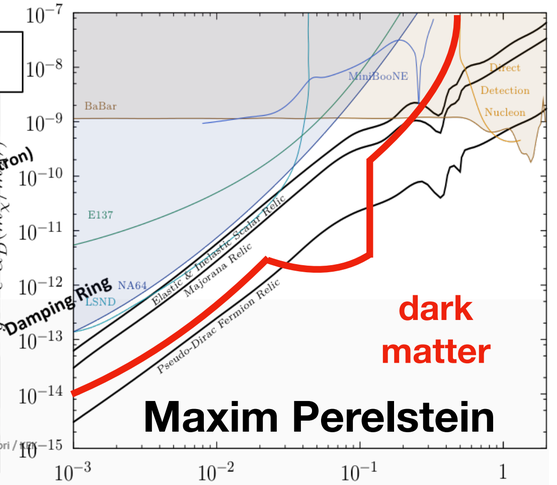

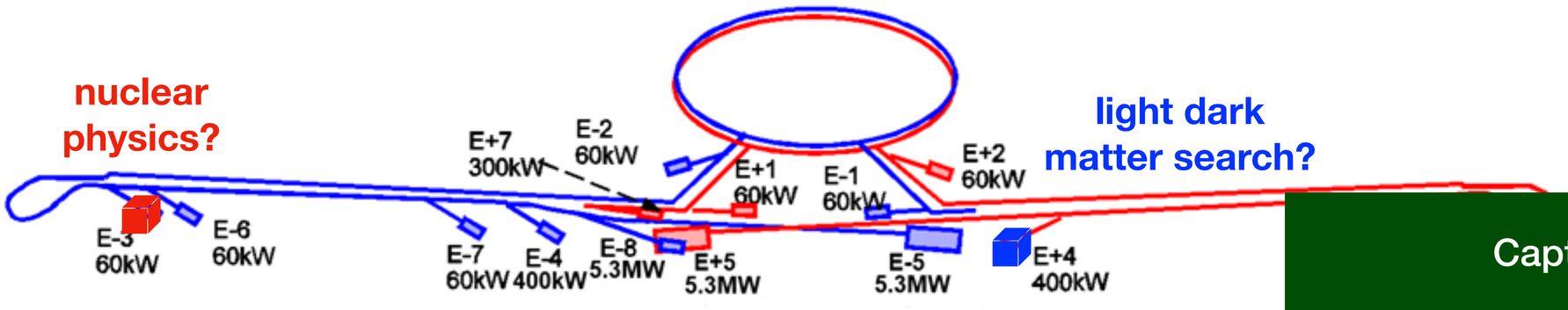

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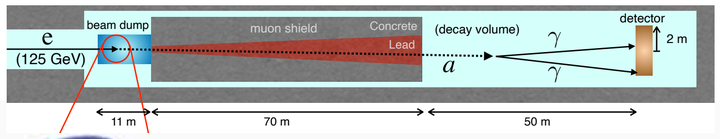

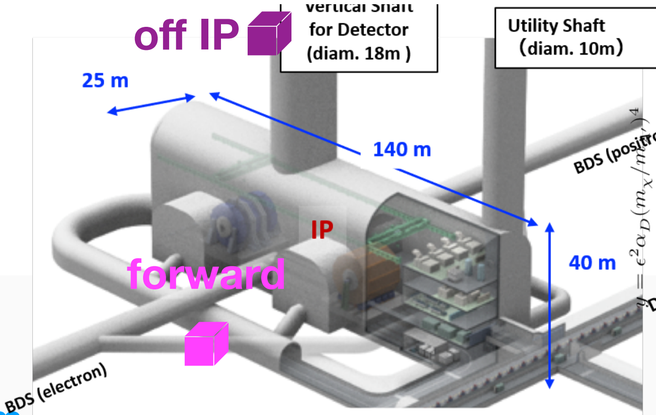

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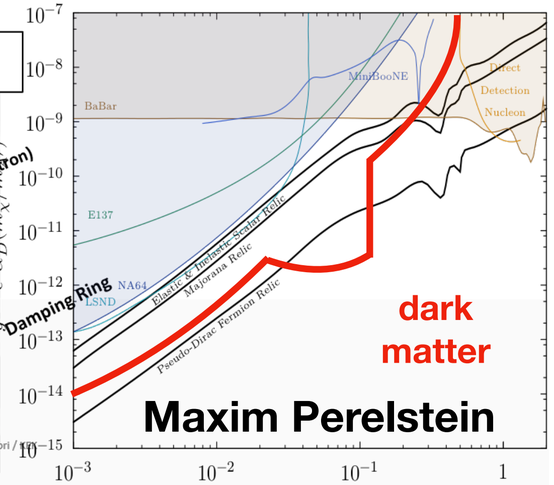
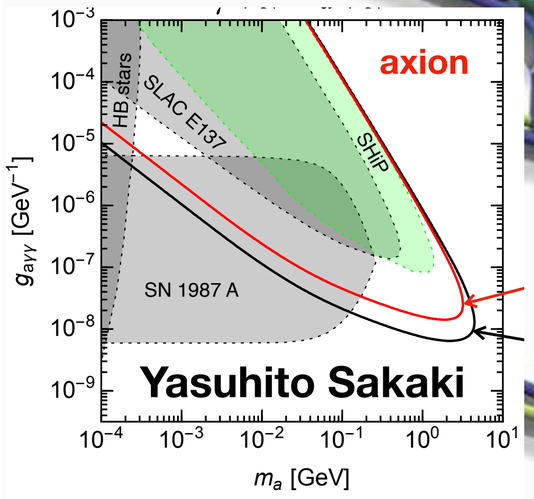
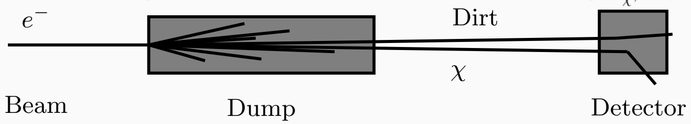
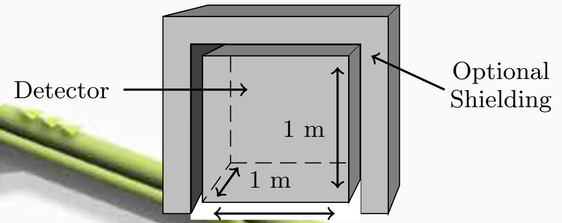




beam dump

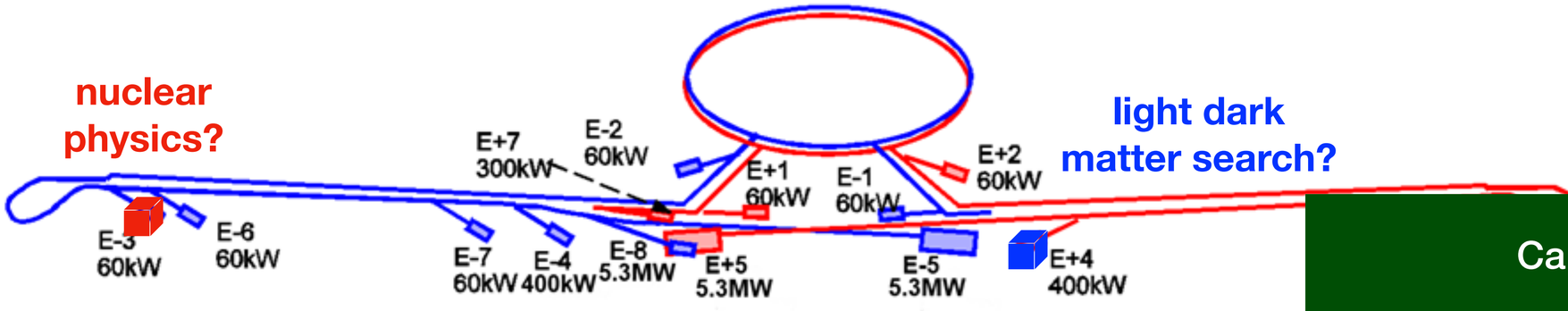
beam dump





nuclear physics?

light dark matter search?

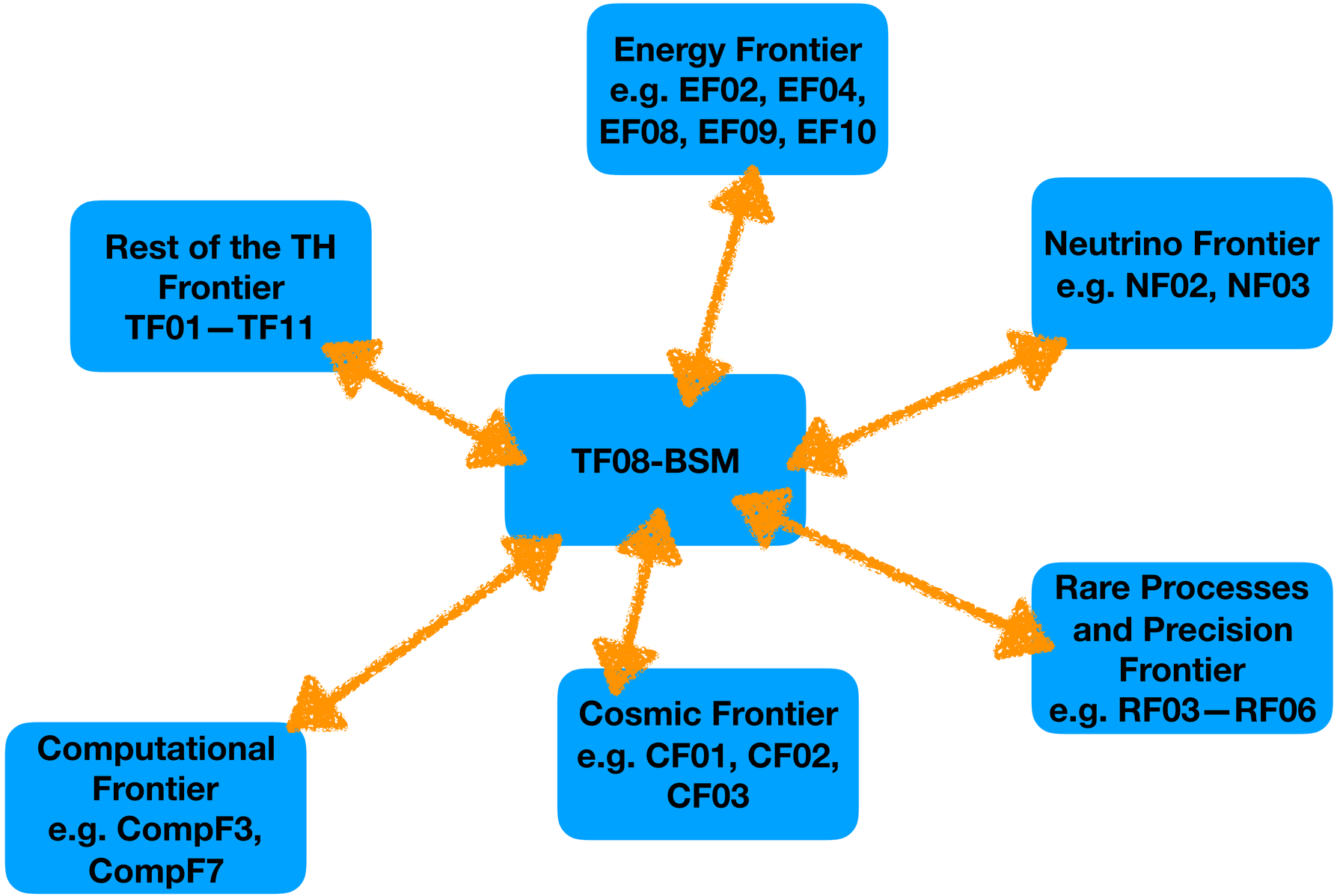


Caption Box


theorist
experiments


colliders
theorists
neutrinos, rare &
precision
cosmology

healthy field!


Energy Frontier
e.g. EF02, EF04, EF08, EF09, EF10
Rest of the TH Frontier
TF01—TF11
Neutrino Frontier
e.g. NF02, NF03
TF08-BSM
Rare Processes and Precision Frontier
e.g. RF03—RF06
Computational Frontier
e.g. CompF3, CompF7
Cosmic Frontier
e.g. CF01, CF02, CF03

Caption Box